B-DER

A Blockchain-based platform for peer-to-peer energy transactions between Distributed Energy Resources

Final report

Utrecht University

Resourcefully
Consulting & management of water & energy resources

energycoin

Public report

Project details

Projectnumber:	1621404
Project title:	A Blockchain-based platform for peer-to-peer energy transactions between Distributed Energy Resources
Coordinator:	Universiteit Utrecht
Partners:	Resourcefully EnergyCoin Foundation
Project period:	1 December 2018 – 31 May 2020

Contact details

This report is created by the project partners. For questions regarding the project, results and follow-up projects you can contact:

Universiteit Utrecht
Wilfried van Sark
+31 30 2537611
w.g.j.h.m.vansark@uu.nl

Subsidy

The project was supported with a subsidy from the Dutch Ministry of Economic Affairs, National EZ subsidies, Topsector Energie – Subsidy Energie en Innovatie (SEI), performed by the Rijksdienst voor Ondernemend Nederland (RVO), within the framework of the TKI-Toeslag 1621/2016 call.

Cover

The picture on the cover © EnergyCoin Foundation.

Summary

Distributed energy resources, such as Photovoltaics (PV) panels and electric vehicles (EV) are increasingly being deployed in the built environment. This requires Information and Communication Technology (ICT) based electricity management solutions to guarantee grid reliability. The prosumer will become increasingly important in this, as he/she can provide crucial services to distribution system operators which may defer grid investments. A key element in this is Peer-to-Peer (P2P) trading, that enables and allows prosumers to trade electricity between themselves.

This project has focused on developed a system in which electricity can be traded. It is based on an integrated blockchain-based energy management platform as an ICT solution that respects physical microgrid constraints and implements a bilateral trading mechanism.

This required the formulation of a distributed optimization problem that respects physical microgrid limitations via an optimal power flow method and that also allows to implement a bilateral trading mechanism. The implementation of the distributed algorithm on a blockchain network for smart contracts has been developed. This can take on the role of virtual aggregator: it performs the consensus step from the alternating direction method of multipliers algorithm to solve the optimization problem in a distributed manner. It also functions as a central agent for distributing required information and data to all other connected nodes (households).

Assessment of several scenarios differing in physical constrains and/trading showed that combining trading mechanisms and grid constraints yields a somewhat lower total social welfare, i.e. costs, while peak imports as well as grid import costs are reduced as compared to the trade-only scenario. The grid constraints scenario, while showing the best results for social welfare, seems difficult to realize since intensive cooperation is required. Furthermore, it does not provide the benefits conferred by the bilateral trading mechanism. Thus, it appears that there are considerable benefits to combining trading with physical constraints when designing energy optimization platforms, especially when comparing to the baseline scenario (i.e., individual optimization without trading or coordination): Import costs are reduced by 34.9%, and peak import quantity is reduced by 60%. Regarding real-life applicability, a trade-only scenario could represent full P2P type markets, whereas a grid-only scenario could represent an energy collective. The combined scenario could represent a middle ground where several downsides of the other scenarios are mitigated.

Regarding the blockchain implementation, we have used the HyperLedger Fabric (HLF) as a permissioned private blockchain solution. The HLF offers the most suitable blockchain configurations for our distributed P2P optimization platform for its customizability, light consensus protocol as well as high security and reliability for the considered case study in a single microgrid or energy community.

Research into the social acceptance of the different scenarios and actual wishes of participants could give further insights into the practical feasibility. The usefulness of the proposed model can be expanded in several ways. First of all, the blockchain implementation needs to be tested for larger networks with, for instance, P2P energy trading between nodes that belong to multiple neighbourhoods or microgrids, in terms of efficiency of communication, security and execution speed. Furthermore, the sensitivity of modelling results to input parameters such as trading coefficients, investment costs and DER distribution could be explored. Also, a detailed techno-economic assessment could be carried out to evaluate social welfare over an extended period of time.

Preface

This final report describes the work performed in the project B-DER (A Blockchain-based platform for peer-to-peer energy transactions between Distributed Energy Resources) as carried out with subsidy by the Ministry of EZ, Topsector Energie – Subsidy Energie en Innovatie (SEI), TKI Toeslag call 1621/2016. The report addresses at great length the results obtained. In addition, a number of project changes are described.

Contents

1. Introduction

The rapid growth and adoption of distributed energy resources (DER) in the distribution network, such as rooftop Photovoltaics (PV) panels and electric vehicles (EV) (see Figure 1), calls for novel management solutions and new business models for coordinating these DER to guarantee grid reliability in the future. Optimally managed DER can help households decrease their electricity bills; provide crucial services to distribution system operators (DSO), such as peak shaving; and enable a large-scale integration of renewable resources into the grid [1].

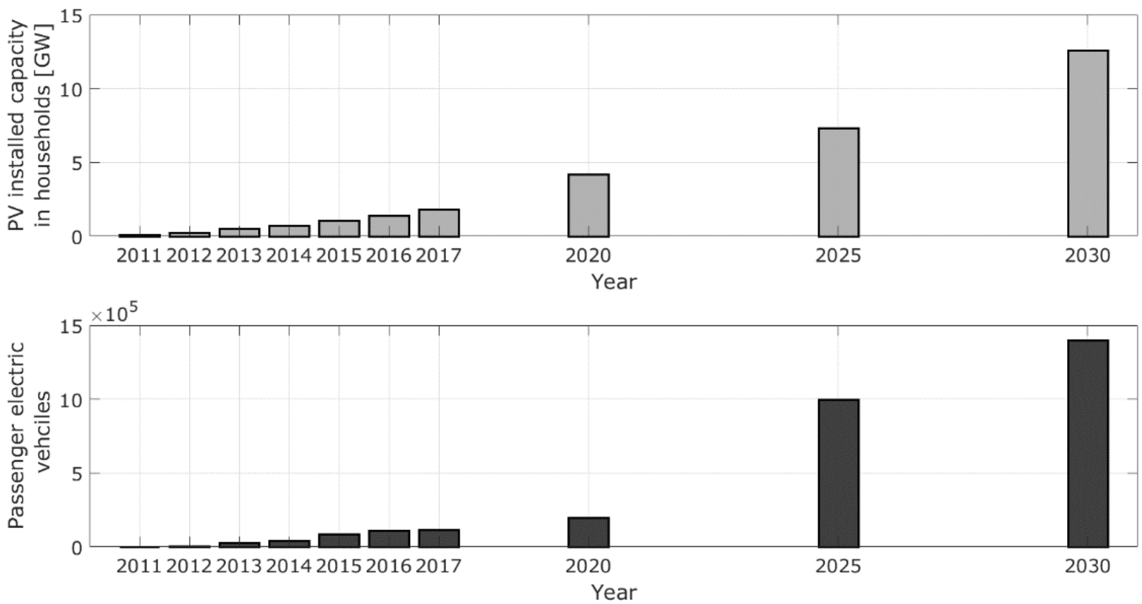


***Figure 1** – Growth of residential PV and passenger EV in the Netherlands [2-6].*

Proposed management schemes for coordinating supply and demand in the distribution network (e.g., demand response) have typically assumed that the operation of DER is centrally managed by an aggregator or a cooperative utility [7]. However, these centralized schemes suffer from scalability issues when the number of DER is large [8.9]. Besides, they are typically met with low acceptance by households due to limited financial incentives, and users' discomfort with centralized control [10]. In addition, considering the policy-induced decreasing monetary benefit of injecting solar power to the grid, reducing grid interaction by optimizing self-consumption and self-sufficiency of PV becomes increasingly relevant for households [11]. For instance, in the Netherlands, the present net-metering scheme for solar power is set to expire in 2023, albeit that it will be replaced by another system that should allow for similar economic payback times for PV system owners.

Consequently, new management solutions of DER in the low-voltage network are urgently needed to provide energy security, reduce the burden on the grid, optimize households benefit from their PV systems and guarantee that projected PV-capacity will be installed despite abolishing net-metering.

The B-DER project developed a novel decentralized energy management platform based on blockchain technology for Peer-to-Peer (P2P) energy transactions between DER in the distribution network and assessed its technical and economic performance on the low-voltage network. A decentralized optimization algorithm has been developed and tested and several blockchain architectures, supported by smart contracts, have been investigated and used for implementing the optimization algorithm to ensure that energy transactions were performed in secure and verifiable manner. This integrated blockchain-based optimization platform enables the control of the network simulation and demonstrates how to address incentive issues for participants while respecting operational constraints of distribution network and DER. Scenarios for operating and managing the proposed platform in real world applications have been proposed and discussed in this project.

1.1. The digital platform and Blockchain

The evolution of the electricity grid is enabled by several advancements in ICT technology. First of all, recent years have seen a large increase in the number of installed smart metering systems in Europe [12]. Analysis of data provided by these meters enables further energy management solutions and smart optimization of energy flows [13]. Expanding on a smart metering system is the home energy management system (HEMS). A HEMS is a system that is capable of balancing power usage in the household by measuring and controlling the operation of all connected electrical assets in a household [14].

Digital platform technologies have shown their disruptive potential in several sectors. Such platforms may raise privacy issues when the platform being utilized is owned by a self-interested third party [15]. The algorithms that run the functionality of the platform are often not transparent for users, and they may be vulnerable to cyberattacks and tampering. The recent emergence of blockchain technology may provide a solution to these problems [15,16]. A blockchain is a type of distributed ledger technology that stores data of transactions in publicly verified encrypted information blocks. Each block is identifiable by its cryptographic hash, and each block's hash references the hash of the block that came before it, forming a link between each block, hence the name "blockchain" [17]. It can be used to connect a large number of anonymous nodes without the need for a central controlling agent.

Blockchain technology utilizes a consensus mechanism to ensure security of the network and allows participants to store and share data in a secure and verifiable manner, even when the identity and trustworthiness of other peers is unknown. The most common consensus mechanisms are the Proof-of-Work (PoW) and Proof-of-Stake (PoS). The PoW mechanism implies a complex verification algorithm which typically requires high energy demand to operate especially in large scale networks, while PoS mechanism reduces the verification complexity and requires less energy and operation costs [16,18,19]. A simplified illustration of how a blockchain transaction works is shown on Figure 2.

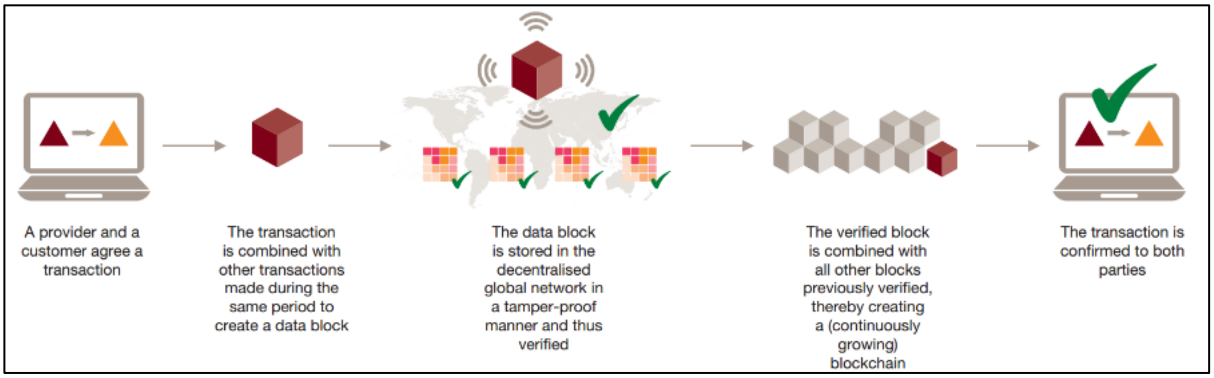


Figure 2 *– Blockchain transaction process (Source [18]).*

Information is stored in sets of data called blocks and verified using cryptographic hashes. Participants can join or leave the blockchain network at any moment without impacting the operation of the system significantly and it is extremely difficult for external attackers to gain control of the blockchain. The clearest application for blockchain has proved to be verification of ownership, as is the case with cryptocurrency [20], but distributed computation between all connected devices is also possible. Extension of a blockchain with smart contract technology expands the utility even further and enables smart optimization in the energy sector [15, 21]. The blockchain architecture can either be a public or a private network. In a public blockchain, participants involved in the network are able to view, verify and make transactions. When viewing transactions, the addresses of the participants making transactions are anonymous. The information they can read is the amount being transacted (e.g., currency or energy) and the time of the transaction. In private blockchains, participants must be accepted into the network and not every node can view, make and verify transactions. These networks are sometimes called consortiums [22].

The application of blockchain technology in the energy sector has been rapidly gaining attention from the scientific community. A large number of studies and initiatives about the use of blockchain in the energy sector are surveyed [15] and blockchain is seen as particularly promising in the area of P2P trading and decentralized energy management, since through blockchain a large number of self-interested actors can be connected and coordinated. The overall conclusion in this survey is that blockchains may provide clear benefits to energy system operations, markets and consumers. This is corroborated in a recent study [23].

The key application of a blockchain-smart contracts architecture in the area of energy lies in its potential to develop a decentralized smart energy supply system [18]. With a set of predefined rules, smart contracts are able to control a network of DER by automatically signaling the system to perform a certain action. For example, smart contracts could autonomously send a defined amount of electricity (i.e., based on the optimization algorithm output) to any household that is willing to buy it for a certain price. These capabilities ensure that each agreed transaction would be done even in the presence of cyberattacks, communication dropouts, or participants joining/departing the system.

The Brooklyn Microgrid project by LO3 Energy and ConsenSys is an example of a project that adheres to a transactive microgrid architecture. It covers three neighborhoods in Brooklyn, New York. Prosumers transact their energy generated by their local PV system through an Ethereum-based private blockchain platform named TransActive™ Grid blockchain [24,25]. The virtual microgrid market is implemented on top of the existing physical grid infrastructure. It aims at increasing the local security of power supply by integrating renewable generation. It also shows that a blockchain can be successfully used to implement local electricity markets. The work in reference [26] expands on this by employing smart contracts on the blockchain network to enable decentralized optimization of an Optimal Power Flow (OPF) problem without a central coordinator. In Australia, Power Ledger [27] runs a peer to peer energy exchange on top of Ethereum, the company held a successful token sale and signed a recent agreement to experiment with partners in the Japanese market. Sponsored by the Ministry of Energy of the Republic of Lithuania, WePower [28] was launched with a token-sale to develop a peer to peer energy exchange on top of Ethereum. Mihaylov et al.]29] describe a protocol for peer-to-peer energy trading on a blockchain.

The potential influence of blockchain on the configuration of the actors in the Dutch electricity system and its ability to transform the existing system is analysed in [30] based on a social network analysis. A blockchain-based system for Peer-to-Peer (P2P) energy trading between households is proposed in [31]. A decentralised optimal power flow algorithm for distribution networks using blockchain-smart contract is presented in [32].

The research to date described protocols and concepts about peer-to-peer energy trading using blockchain and highlighted in a qualitative manner the potential of this technology in decentralizing the energy system. While interesting, the previous research, however, did **not** address the cyber-physical operational constraints of the distribution network and DER and how energy transactions between DER could be performed in an optimal way. Since DER are managed at household level, the question to ask is: how can local decision making of energy transactions guarantee the global optimality of the whole distribution network? This is clearly different from centralized optimization where all DER in the network are managed by a single entity (e.g., an aggregator).

2. Goal and purpose

In the Netherlands, there are no market alternatives at household scale due to the limitations of the Dutch energy policy framework. The net-metering policy has prevented energy exchange, sharing or localized consumption mechanisms. However, this is expected to change in the near future as a policy shift has been announced by the new Dutch government, and actual feeding into the grid of surplus production will receive reduced financial compensation (abolishment of net-metering by 2031). Thereby, peer-to-peer energy transactions between DER becomes a truly viable option for innovative energy management systems market at household scale.

Therefore, this project aimed to develop an optimization algorithm for coordinating DER and implement it on a blockchain-smart contracts architecture. We aimed to assess the technical and economic potentials of the proposed platform for households, charging stations owners and DSO using actual data from a residential neighbourhood in Amsterdam, the Netherlands. We thus aimed to develop an integrated energy management platform that implements solutions in the physical, economic and information layers. The goal of the platform was to optimize the flow of electricity in a distributed manner in a realistic microgrid configuration which features a number of households with access to a variety of DERs.

This assessment would be compared with the uncontrolled operation for current and future scenarios with high DER penetrations (see Figure 1). The actual data that were to be used in B-DER were collected by energy monitors in a running pilot under the previous 3-years EU JPI Urban Energy project (PARENT [10]). This strengthened the project by saving time and cost needed for installing monitoring devices and accessing households' electricity consumption, PV production and EV charging stations data, which are typically considered as sources of risk in these kinds of projects.

The main question was how to perform a decentralized optimization of DER and at the same time guarantee that the whole network is optimized, and how energy transactions between non-trusting participants (e.g. households and charging stations owners) are implemented and verified in a blockchain-smart contracts architecture. The project addressed the following sub-questions:

1. Since DER are managed at household/charging station level, how can local decision making of energy transactions guarantee the global optimality of the whole distribution network? This is clearly different from centralized optimization where all DER are managed by a single entity (aggregator).
2. How can the optimized energy transactions be organized via a blockchain-smart contracts architecture to guarantee a verifiable, secure and transparent operation of the proposed platform?
3. What is the technical potential of implementing this platform on the distribution network (i.e., by matching demand and supply and reducing peak demand)?
4. What is the economic potential of implementing this platform for households and charging stations owners under different pricing schemes that would replace net metering in the future?
5. How are the potentials of the proposed platform influenced by the uncertainty of PV generation electricity consumption and EV charging behaviour?

Optimal Power Flow is used to determine power flows in the physical layer, and a bilateral trading mechanism is implemented in the economic layer. The bilateral trading mechanism provides households with greater control over their trading and allows them to indicate preferred trading partners. It could also be used to enable product differentiation. In the information layer, the model is implemented on a blockchain network with a smart contract acting as a virtual aggregator. Figure x shows the structure of the platform we developed in the B-DER project. The goal of optimization is to maximize total social welfare of all connected actors where the highest social welfare is typically represented by the minimal financial costs. The Alternating Direction Method of Multipliers (ADMM) algorithm is used to solve the optimization problem in a distributed manner. The modelled platform is intended to provide a high degree of independence, privacy and transparency by the implementation on the blockchain network, as well as personal choice and freedom through bilateral trading.

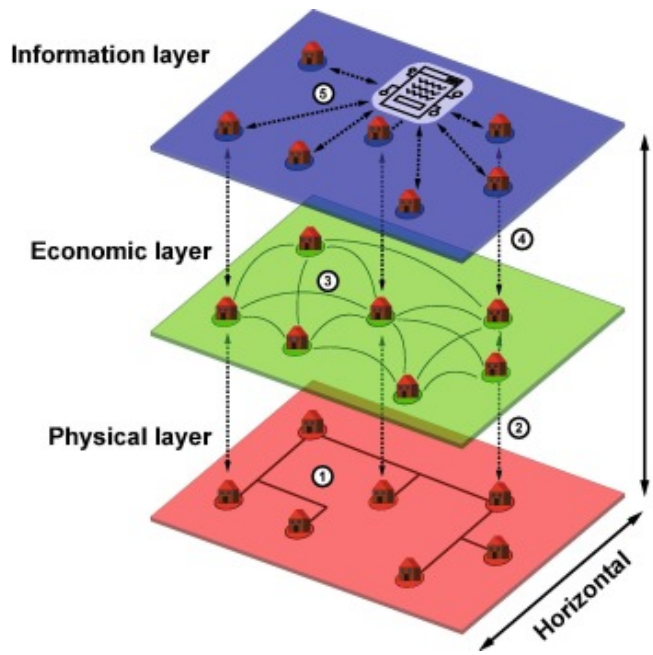


Figure 3 *– Illustration of the different layers of the proposed model and the interaction between them. 1) In the physical layer, power flows in the horizontal dimension between households through grid connections. 2) Information is exchanged in the vertical dimension between the economic and the physical layer. 3) In the economic layer, a trading mechanism is used to enable monetary compensation for power injections and withdrawals into/from the grid. 4) Information is exchanged between the information layer and the layers below. 5) The households send their locally calculated optimal schemes for the economic and physical layers to the smart contract. (Source [31]).*

3. Working procedures

The project was divided into one management work package (WP5) and four innovation work packages (WP1-4). Every work package was further subdivided in several tasks (T). WP1 was a preparatory work package. It contained four tasks in which the project protocol is determined and the input/output data sets are prepared and managed. WP2 was the core work package, as it should design the platform architecture, develop and evaluate the optimization algorithm. In WP3, the implementation on blockchain was to be performed, tested and validated. WP4 assessed the economic and technical performance of the platform. Project management and dissemination is done in WP5. A detailed description of the proposed work is given below.

WP1: Project protocol and data preparation/management

Task1.1 Determination of the project protocol: Within this task, a protocol for conducting the project is developed, setting conditions therefor and for the participation thereto of individual households, with a view to: (1) ensure observance of Responsible Research and Innovation (RRI) principles, (2) adjust project to local conditions (e.g. energy consumption/production patterns, climate conditions, economic situation, etc.), (3) determine responsibilities of project partners, municipality of Amsterdam and Liander, in the context of the project (e.g. soliciting participation, data access, dissemination of information, appointment of contact persons, languages used, etc.), and (4) set forth conditions for involving and evaluating project results with the different stakeholders (households, municipality, DSO and consumers associations). In addition, a template for consent for participation in research is developed and distributed to households. No additional equipment is needed to be installed to run the project since the energy monitors installed in a previous project (PARENT) are exploited in this project.

Task1.2 Input data sets: Resourcefully prepares and manages four input data sets throughout the project:

a) Households electricity consumption data: this data set includes the consumption profiles of households located in the neighbourhood. Additional meta data, such as households' size, type and number of inhabitants, will also be included in this data set.
b) Households PV production data: this data set includes the PV production profiles of households located in the neighbourhood. Additional meta data, such as PV panels size, age and technical characteristics will also be included in this data set.
c) EV charging stations data: this data set includes the consumption profiles of EV charging stations located in the neighbourhood. In our project, only the aggregated demand of EVs in each charging station is needed and there is no need to disclose details about cars ID, type, plug in/out time, etc.
d) Electricity pricing data: this data set includes the electricity prices in the Netherlands in wholesale and retail markets.

Task1.3 Output data sets: Resourcefully and ECF prepare and manage two output data sets throughout the project:

a) Output schedules of the platform: this includes households and EV charging stations schedules for electricity consumption/trading after being optimized using the optimization algorithm, registered and verified on blockchain.
b) Assessment results: this set includes the platform economic and technical assessment results for different penetration levels of PV and EV currently and in the future.

Task1.4 Back-end development: The Back-end consists of IT system servers and the server-based code required to power the platform development in WP2 and WP3 and input/output data sets storage in T1.2 and T1.3. This task develops back-end code in Python that implements the optimization algorithm on blockchain. Resourcefully and ECF validate platform functionalities and system debugging.

WP2: Platform design and optimization algorithm

Task2.1 Platform architecture design: This task designs a system architecture that considers hardware, software and scalability requirements. The system architecture indicates how the different components of the platform fit together and interconnect.

Task2.2 Development of the optimization algorithm: In this task the optimization algorithm is developed. It is a distributed optimization algorithm that optimizes the operation of a network of DER and guarantees local and global optimality of DER of all participants. A residential area in Amsterdam is considered that consists of several households, each with a PV system, a smart meter and an energy management system, and a number of EV charging stations. These creates a network of DER each with its own electricity consumption and energy production profiles. The optimization minimizes households' electricity costs from the grid and maximizes benefit from their PV system while at the same time minimizes electricity costs for EV charging stations owners. The optimization also considers the distribution network voltage and power lines constraints

Task2.3 Evaluation of the optimization algorithm performance: This task evaluates the performance of the optimization algorithm in terms of tractability (i.e., finding a global optimal solution) and efficiency (i.e., in terms of computational time). The scalability is tested for different future scenarios where a high number of DER will be integrated into the distribution network. The final objective is to evaluate and present the performance of the optimization algorithm for different penetration levels of DER now and in the future.

WP3: Implementation on blockchain

Task3.1 Linking the optimization algorithm with blockchain: After solving the optimization problem of all DER, optimal schedules for energy transactions are available. These transactions should be contracted between the DER in a distributed fashion. To do so, the transactions between DER will be communicated with a cloud-based private blockchain, to which households are connected via their energy management systems, and converted to smart contracts. All households in the network will verify the smart contracts, and then they will be recorded on blockchain.

Task3.2 Evaluation and verification of the platform performance: This task tests the functionality of the final platform and ensures that peer-to-peer transactions are valid and the final optimization is ensured and correct.

WP4: Platform assessment

Task4.1 Economic assessment of the final platform: This task calculates the economic potential of the proposed platform for households and EV charging stations in the neighbourhood based on the cost savings achieved when optimizing the usage of DER, and the profit made when trading energy with each other.

Task4.2 Technical assessment of the final platform: This task quantifies the technical potential of the proposed platform for DSO based on the achieved balancing between supply and demand, and the reduced demand from the grid.

Task4.3 Uncertainty analysis: This task analyses how the economic and technical potentials of the proposed platform are influenced by the uncertainty of PV generation, electricity consumption and EV charging behaviour.

WP5: Project management: During the project, several meetings are organized during which the partners shared the progress of the results. In addition, regular coordination has taken place via predominantly bilateral meetings and telephone contact. Quarterly the financial status of the partners was requested. Dissemination activities have taken place primarily via participation in (inter)national conferences and publication of papers in scientific journals.

4. Results

The results will be described per workpackage rather than per task, and have led to two key publications [31,32].

4.1. WP1: Project protocol and data preparation/management

4.1.1. Responsible Research and Innovation

This project aims to contribute to solving the critical challenges facing society, particularly 'Secure, clean and efficient energy' as well as 'Climate action, environment and resources' as defined in the Grand Challenges formulated by the European Commission. Optimised management of Distributed Energy Resources (DER) in residential areas will encourage higher uptake of solar PV systems and electric vehicles (EVs) by households, increasing their self-sufficiency on clean energy while more efficiently using the grid infrastructure. The increased uptake of local renewable energy sources and EVs will reduce reliance on fossil fuels both for homes and for transport, directly leading to greenhouse gas abatement.

Apart from the main project participants, this project involves the Municipality of Amsterdam, ElaadNL (the Dutch knowledge and innovation centre in smart charging infrastructure) and Liander (the local Distribution System Operator (DSO)) from the early stage to discuss methodology and platform design and to share the assessment results to make sure that their experience and feedback are included. This ensures the project results are relevant to all stakeholders.

By assessing the technical and economic potentials of the platform for all stakeholders, including households, EV charging station owners and the DSO, and including input from the municipality from an early stage, this project intends to build a platform that not only contributes to environmental sustainability but will be sustainable and scalable from an techno-economic perspective as well, while being focused on society's needs.

The B-DER project involves a diverse range of actors, from academic to infrastructure operator to municipal government, to ensure an inclusive process of research and innovation. The project aims to be open and transparent by communicating the design, methodology and results to the public through various channels, as well as opening up access to the platform at the end of the project. The methodology of the project is responsive to the identified technical, economic, social and environmental needs of the stakeholders, and will be adapted to ensure the best possible outcomes.

Real-world data used in this project is collected with the informed, express consent of participants, and is anonymised to protect the privacy of participants. Data management is conducted by Resourcefully and sharing of collected data is not allowed except for the purpose to which consent was given. The data is be owned by the B-DER consortium for the purpose of project delivery. Nevertheless, to allow for maximum utilisation of the project findings after the end of this project, the B-DER consortium aims to make the design, modelling and implementation of the platform as well as the project results available to the scientific, industrial and general public via scientific articles, partners' web pages, blog posts and workshops.

This project is based on actual data from a residential neighbourhood in the city of Amsterdam (The Netherlands) collected by energy monitors in a running pilot under the previous 3-years EU JPI Urban Energy project (PARENT). Household consumption, PV production, and EV charging station data from these monitors is made available and used in the project, allowing development and implementation of the optimisation algorithm and transactive platform based on actual local data. An example is shown in Figure 4, which is a screenshot of the actual website www.prosumers.nl. In this way, local climatic conditions are taken into account whereby household energy consumption is highest during the cold winter months due to space heating, while PV production is at its lowest due to reduced solar irradiation. The data is from middle-class households in Amsterdam with a typical connection to the Liander grid, representing the typical economic conditions for many households in the city. Additionally, this project draws on the experience of Resourcefully's creation of a neighbourhood energy simulation and dashboard ("eflows") for the municipality of Amstelveen. This was used to assist the municipality to plan for their future new-build neighbourhood by visualising heat pump demand, solar PV generation and EV charging and optimising them for self-consumption, thereby reducing grid congestion.

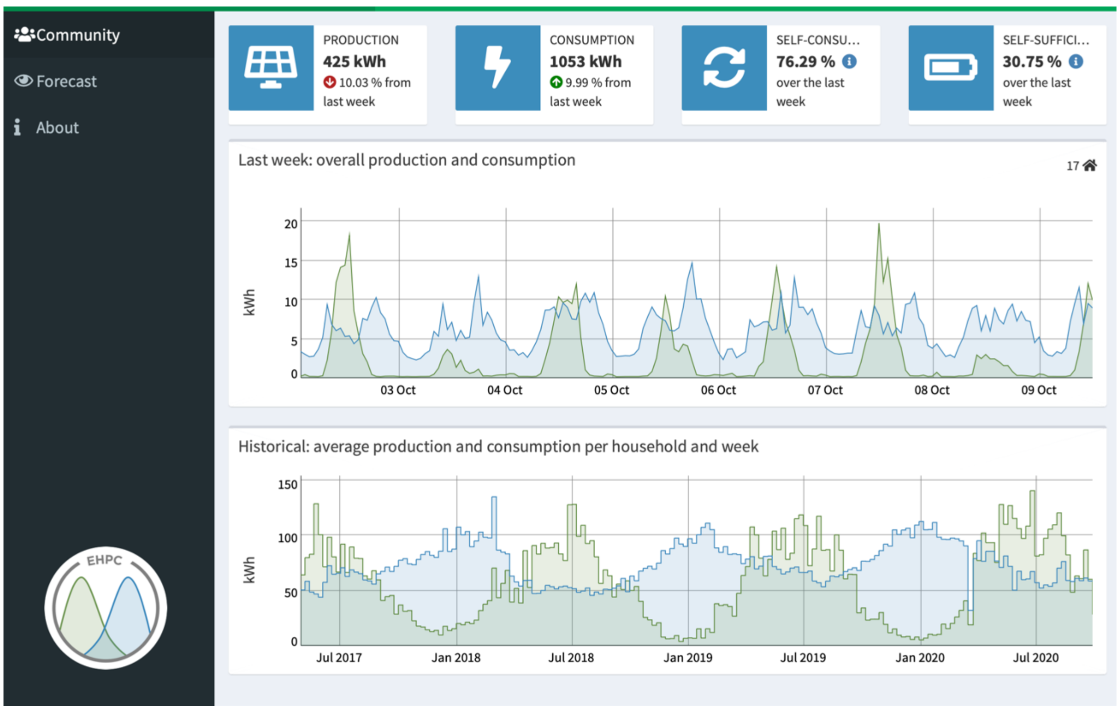


Figure 4 *– Screenshot of dashboard in use at the Amsterdam East Harbour Prosumer Community, managed by partner Resourcefully.*

The responsibilities of the project partners are further detailed in Table 1.

Table 1 *– Responsibilities of project partners*

Item	Utrecht University	Resourcefully	EnergyCoin Foundation
Solicit household participation		X	
Data management		X	X
Data access	X	X	
Public dissemination of information			X
Scientific publication of results	X		
Develop optimisation algorithm	X		
Provide blockchain infrastructure			X
Develop blockchain smart contracts	X		X

4.1.2. Market changes and regulatory issues

As shown in Figure 3, several layers exist in the electricity system, a physical, an economical, and an information layer. The physical layer connects sources of electrical energy and consumers receiving that energy. In the financial layer producers are paid, wholesalers and traders sell forward and consumers pay for the energy they have consumed or will consume.

Responsibilities for grid management in the physical layer are distinguished using voltage levels (high, medium, low) and we discern Transmission System Operators (TSOs) for high-voltage (HV) grids and Distribution System Operators (DSOs) for other voltage levels (MV, LV). DSO's in the Netherlands have no direct financial or retail relationship with consumers. They do have a service relationship in the electrical layer though; if consumers experience technical difficulties or brownouts and blackouts the DSO is responsible. Grid management is a publicly owned function, the cost of which is socialized via grid tariffs. Retail ('energy suppliers') in the Netherlands is a liberalized market.

We are in a transitional period after the simple top down energy supply from producer to consumer in the electrical layer and from energy supplier to consumer in the financial layer. The availability of renewable energy sources that are relatively affordable and easy to install like solar but also wind energy when we compare it to traditional power plants based on coal, gas or nuclear have changed the landscape. Consumers increasingly are becoming small producers of energy, nowadays called 'prosumers'. For larger installations citizens increasingly join forces to invest in and create solar fields and even wind parks. Many new energy collectives and cooperatives have been established and still are. In many cases these are subsidized or helped by various government schemes like SDE subsidy, offsetting, lower energy taxes, 'postcoderoos' and the recent 'experimentenregeling'.

Having a 'commons' in a community; land where everyone could feed their cattle or grow food has a long history. This concept came back in new forms because of the internet. People realized there could be a common digital space where one could read, enjoy and download content created by sometimes known, but often completely unknown, creators from all over the world. People soon realized that the peer to peer ('p2p') concept could also apply to different forms of services and content. Selling secondhand goods and increasingly also new goods via online auctioning like Ebay was soon followed by private holiday accommodation sharing via AirBnB and private taxi services via the likes of Uber. In most of these cases the peers are known to each other and can rely on information shared by earlier users ('feedback') in what has become a very powerful self-regulated control mechanism. However, some view that peer to peer means that users are directly interacting with each other, without an intermediate entity [33]. It could be argued that it would only be a matter of time before both movements would be combined and people would realize that you could sell energy direct to other consumers instead of being limited by offsetting schemes which do not even exist in the same way in many countries.

However, energy (electricity) has a much more traditional, strict and all-encompassing regulatory 'layer' and framework than transport and hospitality. Understandably since it always was mainly operated by public bodies and large companies. It simply never had the finer granularity and private markets that selling goods and services, taxi and tourism always had. And another aspect is of course the societal and legal requirements that the lights should never go out and consumers have the right to purchase all energy they need at any time. An important example of this regulation is that anyone who supplies energy to consumers (as opposed to 'sell back' to the grid) needs to have a supplier license and needs to have balance responsibility (‘programma verantwoordelijkheid’) or has this outsourced to a balance responsible party [34]. Simply put; in the financial layer all energy customers have consumed needs to be purchased in advance. If one has purchased more than was necessary margins are gone or even losses made. If one has purchased less than one’s consumers have used one can expect heavy fines by the authorities of even ultimately loss of license. Grid management takes care of the electrical layer and makes sure that all energy consumers use is always available, and the electrical balance of 230 V and 50 Hz is maintained at all times.

The question arises as to how do we integrate 'prosumers' in a traditional electricity market? They are usually subject to regulated remuneration schemes only. EU policymakers are helping by acknowledging the important role of consumers and prosumers as well as aggregators of those groups in the transition that has become necessary to move away from fossil fuels and one-directional markets. We see wording like 'consumer centred' and 'putting consumers at the heart of the energy market' to avoid rising costs of backup generation and allow consumers to benefit from participation in the market. The EU Commission thus foresees empowering consumers as essential part of the energy transition [34]. This also requires energy law, as a discipline, to support that and move away from the traditional 'silo thinking' which defined actors and their rights and responsibilities along a conventional supply chain as described above. This framework had been developed on policy goals to ensure secure, competitive and sustainable energy supply. It is clear that these goals can conflict, and this is sometimes referred to as 'energy policy trilemma' [35].

Renewables, solar and wind, whether they are organized top-down or by prosumers are intermittent. Their generation profiles do not naturally match unless efforts are made to explicitly match them. Simply increasing renewable production does not lead to the desired low-carbon society. One has to make choice between costly grid improvements and more balancing reservation capacity or optimizing the balance between demand and supply profiles, also referred to as a smart grid. Improving flexibility in consumption profiles to move away from demand-driven to supply driven energy use is necessary [36]. Technically as much as socially this needs a thorough understanding of demand-side aspects. Technically by smart metering, energy storage, electric vehicles and socially by giving consumers and prosumers the right tools, transparency and feedback to create the necessary energy literacy and co-operation.

EU policy has been developing in support of this. It has resulted in the introduction and acknowledgment of the term Renewable Energy Communities [37] and Citizen Energy Communities [38]. Although the latter originally would be allowed to manage their own part of the grid through the wording 'countries shall allow' this has been amended into 'may allow' Nevertheless an import piece of experimentation space for the statement in the heading above. Arguably in a country where retail and grid management are either both public or both privatized, optimization is easier. In the Netherlands retail is private and grid management is and will stay a public function. Maybe especially because of this we needed experimentation space that bridges both spheres and puts the community or cooperative at the helm of their own part of the energy transition, albeit in a safe manner and without opening the door to tax avoidance or evasion. Four years ago, some enlightened architects in ministries (economic affairs, finance and tax and related bodies like RVO) created the 'experimentenregeling elektriciteitswet 1998 en gaswet' and its subsequent Besluit [39]. This has allowed cooperatives and associations of house/apartment owners (VvE) exemptions so they could supply energy to their members and optionally also govern their own part of the grid. Early 2020 the new regulation came into effect, which allows much more exemptions, also from the gas laws. Now almost all legal bodies can request exemptions, including aggregators, grid operators, energy suppliers. Finally, there are more Act articles feasible to have exemptions from. Experiments can also be larger, up to 10.000 (and even 100.000 when proven to be necessary) connections. For any project aiming to experiment with peer to peer or peer to commons having these exemptions is necessary unless another intermediary has a supplier license.

Of special interest here is to focus on projects using blockchain. There are some where decentralized and non-governed ICT systems such as blockchain (a distributed ledger system instead of a centralized database) seem to be used because of the sheer freedom of regulation. There are also many that are in fact a new form of investment/crowdfunding; Initial Coin Offering or ICO's where the underlying aim is to raise the value of the coin by creating successful projects on top of the system. More interesting and relevant are the projects where a new solution to real world problems are sought and explored. There has been a rise in recent years in the number of domestic consumers generating, storing and selling electricity, thanks to a decline in the cost of renewable energy technologies, further accommodated by the availability of smart meters and new forms of storage. The evolution towards a low carbon decentralized system in which prosumers inject intermittent energy into the grid is challenging to manage. It is here that peer-to-peer energy trading using distributed ledgers can facilitate the balancing of demand and supply at local level. The complexity can be solved by the use of artificial intelligence and 'smart contracts' that automatically execute when the contract conditions are met.

As mentioned above we need to make a distinction between 'public' and 'permissioned' blockchains, the latter is restricted to approved participants by a central party which also determines the governing rules. In a critical national infrastructure like energy this seems more feasible than the former [40]. A regulatory framework around this needs to combine the three layers mentioned above, physical, economical and information (data); a unique level of complexity but also the opportunity to optimize the energy transition in all layers.

4.2. WP2: Platform design and optimization algorithm development

Any platform to be developed in this project is supposed to enable peer-to-peer energy transactions between households with either energy generation or storing capabilities, see Figure 5. In order to do so in a **scalable** manner, the best option is to create a **decentralized** system that would have some sort of a global logic in the form of the smart contract. This **smart contract** would guarantee global optimality as well as a set of rules that would have to be obeyed by each user within the system. In addition to this, this distributed system must be **secure and reliable** with good performance especially when it comes to **transaction speed**.

The above implies that the best infrastructure for this project would be some sort of a blockchain platform. Since one of the key benefits of this project is energy efficiency, it would be mandatory to have an **energy efficient consensus mechanism** between nodes. When it comes to privacy, having a **private blockchain** with the ability to make it public would be considered being an advantage.

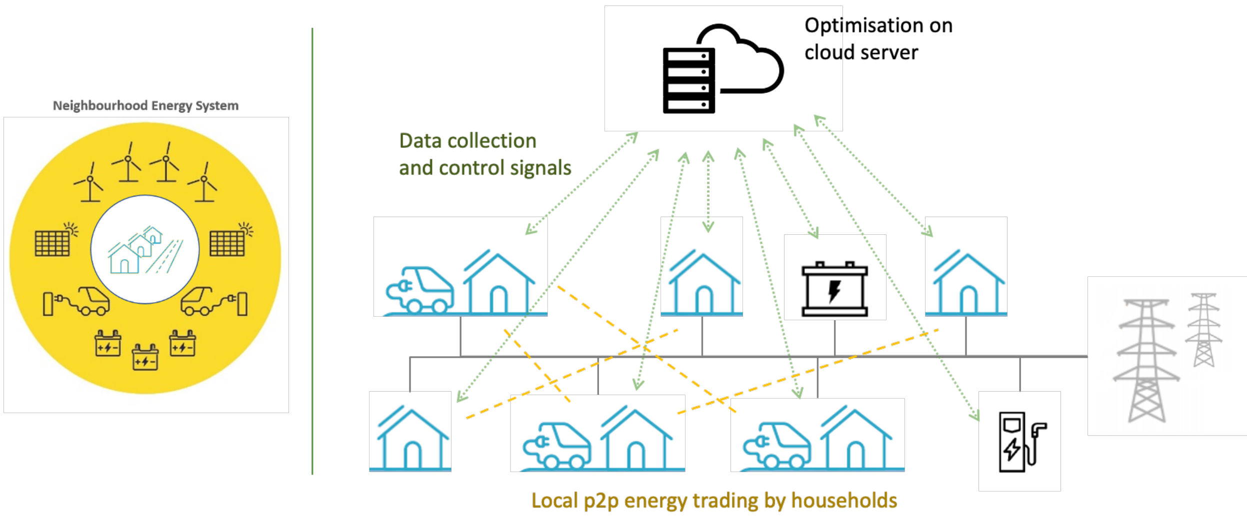


Figure 5 *– B-DER system architecture.*

4.2.1. Blockchain platform analysis

Having the premises in mind, this section provides an analysis of potential blockchain platforms. The following **properties** will be analyzed for each platform:

1. **Scalability** - how does a blockchain platform behaves having a large number of transactions
2. **Smart Contract support** - does platform have the ability to apply a custom set of rules into the blockchain
3. **Security** - how resilient blockchain is when it comes to potential network corruption
4. **Reliability** - information about the level of certainty that blockchain will not fail over time or decline transactions upon various circumstances
5. **Transaction speed** - how many transactions can be written into blockchain per second
6. **Consensus mechanism** - information on whether the mechanism is energy efficient or not
7. **Privacy** - information on whether blockchain is public or private. From a technical perspective, the main advantage of a private blockchain would be the ability to highly customize the blockchain configuration based on your business requirements as well as to prevent malicious behavior on the network. The security of transactions within the blockchain is irrelevant in this context - since they are secured regardless of the blockchain privacy
8. **Cost** - analyze a platform operational cost

Since there are many blockchain platforms, we have narrowed down the potential platforms to:

- **EnergyCoin**
- **Ethereum**
- **Hyperledger Fabric**

4.2.1.1. EnergyCoin

EnergyCoin[1] is a **public** blockchain platform that is working on Proof of Stake consensus mechanism which can be considered as **energy efficient consensus** mechanism. It is considered **scalable**, and each new node would have to download around 1Gb of historic data in order to synchronize with the rest of the nodes. When it comes to transaction speed, as with every other public blockchain, it has arguably **low speed** for enterprise standards. The biggest deal breaker for this solution is its **questionable reliability and security** due to old codebase. It **does not support smart contracts** out of the box - so it would be necessary to create a third-party application on top of the existing nodes in order to apply business rules, as well as to make changes within the platform itself. Compared to other solutions, this platform has **moderate operational cost** that revolves mostly around third party application maintenance and node size and traffic.

EnergyCoin Advantages

- Energy efficient consensus
- Scalable
- The team is familiar with the EnergyCoin source code
- EnergyCoin brand might be interesting for the project

EnergyCoin Disadvantages

- Security issues
- Low transaction speed
- Potential reliability issues
- Requires a third-party app on top of a node as a smart contract replacement
- Lacks functionality within the platform itself

4.2.1.2. Ethereum

Ethereum[2] is a **public** blockchain platform that is currently working on Proof of Work consensus mechanism which can be considered as **energy inefficient consensus**. It **has smart contract support,** but **bad scalability**. Ethereum is considered as the best public smart contract based blockchain, but due to flaws like **low transaction speed** and **unstable transaction fees**, it didn't live up to its hype when it comes to enterprise applications. Even though there were security issues three years ago, the Ethereum blockchain proved itself **secure** over time. The long awaited Ethereum 2.0 is about to be released within its initial phase - providing Proof of Stake consensus mechanism with some scalability improvements via sharing, but the question remains how it would that benefit performance. When it comes to cost, it has **high operational cost** due to potential high transaction fees, as well as large unnecessary traffic and size within nodes.

Ethereum Advantages

- The best smart contract available when it comes to public blockchains
- The most widespread system of that type
- Easy to create a cryptocurrency (tokenize) if necessary
- Secure

---

[1] https://www.energycoinfoundation.org/en/energycoin/
[2] https://ethereum.org/en/

Ethereum Disadvantages

- Bad scalability
- Unreliable due to transaction fee fluctuation
- Low transaction speed
- Even though it is considered decentralized, it's architecture tends to create a centralized environment
- Web3, which is the Ethereum API is considered unstable
- High operational cost

4.2.1.3 Hyperledger Fabric

Hyperledger fabric[3] is a **private** blockchain platform built by Linux foundation. The biggest benefit of this platform is that it is highly customizable depending on the business case and its unique architecture with **energy efficient** consensus mechanism that provides **fast transaction speed** with **high security and reliability**, but with a tradeoff - users have to be identified within the system. It **provides smart contract support** in the form of chain code that can be written using the most popular programming languages. When it comes to cost, it has **moderate operational cost** that revolves around peers and their traffic as well as services that has to be run as a consensus replacement.

Hyperledger advantages

- Highly customizable
- Highly scalable
- Highly secure due to its permissioning and identity management system
- Approved by main industry brands, including IBM, SAP, Intel, Cisco, etc.
- Considered as the best smart contract based blockchain platform
- Much faster transaction speed compared to public blockchain platforms
- Can be public if necessary, by providing a REST endpoint

Hyperledger disadvantages

- High customization also implies high complexity
- Users cannot be anonymous
- The fact that the block generation process is done in the absence of peer nodes makes this platform somewhat centralized

4.2.1.4 Choice

Each of these platforms has its pros and cons and essentially by selecting one of them, something from the other platform has to be excluded. Blockchain technology has not matured enough to be secure, fully decentralized and high performing at the same time; picking a platform means not taking advantage of one of these three characteristics. Based on the project premises, the assumption is that the **security and high performance in terms of transaction speed are considered as the most important while also being able to scale to a large number of users and nodes**. For that reason, based on the analysis as summarized in Table 2, the conclusion would be to select the **Hyperledger Fabric** as the Blockchain platform for further development of the B-DER project. This platform covers most of the premises required for this project,

[3] https://www.hyperledger.org/use/fabric

while the tradeoff is its strict user identity nature and its unique architecture that, while providing key advantages in terms of scalability, performance and security, creates a partially centralized system.

***Table 2** – Comparison of blockchain platforms.*

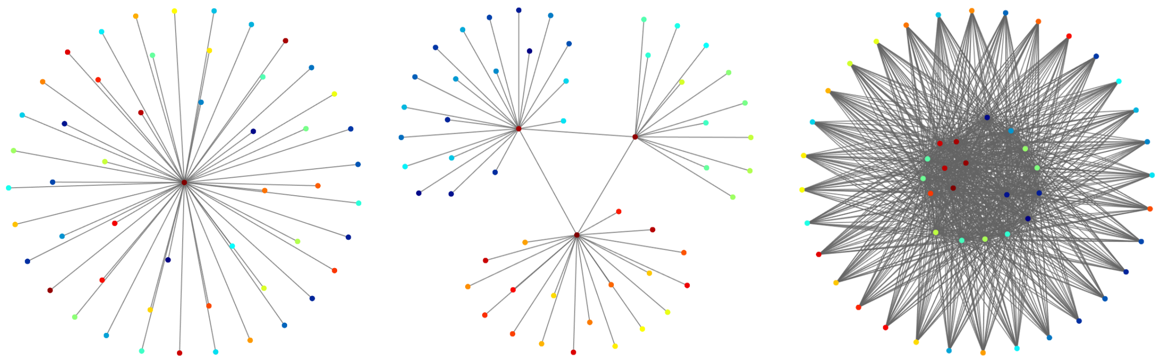
Platform	Scalable	Smart contract support	Secure	Reliable	Fast tx speed	Green consensus mechanism	Private	Operational cost
EnergyCoin	✓					✓		Moderate
Ethereum		✓	✓					High
Hyperledger	✓	✓	✓	✓	✓	✓	✓	Moderate

4.2.2. Algorithm development

We aimed to develop an integrated energy management platform that implements solutions in the physical, economic and information layers (Figure 3). The goal of the platform was to optimize the flow of electricity in a distributed manner in a realistic microgrid configuration which features a number of households with access to a variety of DERs. As stated above, the main question was how to perform a decentralized optimization of DER and at the same time guarantee that the whole network is optimized, and how energy transactions between non-trusting participants (e.g. households and charging stations owners) are implemented and verified in a blockchain-smart contracts architecture.

In the physical grid, the optimal injections and withdrawals must be found while respecting physical constraints. A common way of doing this is formulating an Optimal Power Flow (OPF) problem [41]. The objective of an OPF problem is typically to minimize operation costs. OPF is a mathematical optimization problem that finds the optimal power injection levels and derives branch power flows and voltage levels in the process. OPF problems can be solved for both DC and AC systems and many scientific studies have recently used OPF in a microgrid context. For instance, one particularly interesting study implements an AC-OPF problem on a blockchain platform for decentralized optimization [26]. The work in [42] designs a blockchain-assisted energy crowdsourcing system where the crowdsourcer manages the network and requests tasks from prosumers who could also trade energy within the distribution network.

In the economic layer, we use a recently formulated unified prosumer P2P market model [43]. This scheme may be operated with both bilateral trades and a centralized pool market, and provides an option for participants to declare preferred trading partners by including a trading penalty. A bilateral trading mechanism may provide benefits over the use of locational marginal prices, since it provides participants with an extra degree of freedom and control over their trading. Figure 6 depicts three options for trading. Participants in the market are represented by nodes (colored). In Figure 6a, a radial decentralized market is shown. Participants do not disclose their assets' information but negotiate with a central agent to minimize their energy costs. Energy communities (Figure 6b) can be seen as connected smaller pools, where market makers, or community managers, operate as interfaces with the outside world. P2P trading is depicted in Figure 6c. In the information layer, we will apply blockchain technology, linking to the work done earlier [24,26].



(a) Pool (b) Connected communities (c) Peer-to-peer

***Figure 6** – Decentralized electricity market layouts [43].*

4.2.2.1 Model setup

The proposed platform is designed to function on a microgrid network that features consumers and prosumers with access to privately owned EVs, solar PV installations and battery systems. It functions as a day-ahead energy scheduling platform, and every prosumer household is considered as a separate node on the network. Households are able to trade their excess or deficit electricity budget between them and can indicate preferred trading partners by assigning bilateral trading coefficients to individual trades. Participants act in a mostly self-interested way, but also contribute to the balancing and management of the mi- crogrid, which may involve some sacrifice of self-benefit. The combined optimization problem is formulated in a distributed form using the ADMM algorithm. Finally, the distributed optimization problem is implemented on a private blockchain test network by porting part of the algorithm's functionality to a smart contract. Detailed descriptions can be found in our published work [31,32]. Different versions of the platform are tested by using various scenarios that include and exclude the grid constraints and the trading mechanism.

4.2.2.2 Grid and household setup

The microgrid considered in this study is modelled as a radial Low Voltage (LV) network over a number of timesteps T, indexed by t = 0, 1, ...,T. It can be represented by a set of nodes $\mathcal{N}$, indexed by i = 0, 1, ...,n, and connecting lines $\mathcal{L}$, indexed by l = 0, 1, ...,L. Node 0 is designated as the root node. A node in $\mathcal{N}$ can be either referred to with its index number i or as a neighbouring node of another node j. In this relationship, j is defined as the node that is closer (i.e. fewer connecting lines) to the root node. As such, j is called the parent node of i, and can be referred to as $\pi(i)$. In similar fashion, node i is called the k-th child node of j, and can be referred to as $\delta_k(j)$. Due to the radial nature of the network, every node only has one parent node. A node can have multiple children, and the set of children nodes of node j is referred to as $\delta(j)$, indexed by k = 0, 1, ...,c. For simplicity, every line in is designated to have the same index number as the connected child node. In every line *i*, the complex impedance is denoted as $z_i = r_i + ix_i$, where *r* and *x* are the resistance and reactance in the line.

All households in $\mathcal{N}$ have access to a connection to the grid. Power is fed into and withdrawn from the microgrid through these connections. Power is imported from the utility grid at the root of the network, and is designated as $p_{i,t}^{g}$.The costs of withdrawing power from the external grid at time *t* is represented by κ_t. The cost function for each household *i* in timestep *t* can then be formulated as:

$$C_{i,t}^{g}\left(p_{i,t}^{g}\right) = \kappa_t p_{i,t}^{g}, \quad \forall\ i, t. \tag{1}$$

Every household also has a fixed real power load $p_{i,t}^{l}$ and fixed reactive power load $q_{i,t}^{l}$ that are uncontrollable. Controllable reactive power generation $p_{i,t}^{g}$ is assumed to be available to those households that have access to solar PV. The generation of real and reactive power is constrained within upper and lower limits as follows:

$$\underline{p}_{i}^{g} \leq p_{i,t}^{g} \leq \overline{p}_{i}^{g}, \quad \forall\ i, t. \tag{2}$$

$$\underline{q}_{i}^{g} \leq q_{i,t}^{g} \leq \overline{q}_{i}^{g}, \quad \forall\ i, t. \tag{3}$$

Other assets that are available only to some households but not others include solar PV, EV and battery systems. The availability of solar PV yields a fixed, uncontrollable power generation $p_{i,t}^{PV}$. The availability of EV and battery systems yields additional constraints. An EV is considered to be a shiftable load where both the time and quantity of the charging power $p_{i,t}^{ev}$ can be controlled. Total daily charge must equal the daily charging demand E_i^{ev}, as can be seen in Eq. (4) and the EV charging efficiency is given by η^{ev}. Furthermore, EV charging rate is constrained within upper and lower charging limits. Vehicle-to-Grid technology is out of the scope of this research. A binary parameter $\omega_{i,t}$ i,t is used in Eq. (5) to indicate the timeslots at which the EV charging can be scheduled. It should be noted that this modelling of EV charging patterns is simplified and not a fully accurate representation of real behaviour. Still, for the current purposes of evaluating performance of the proposed platform with the presence of flexible load, this is viable and sufficient.

$$\sum_{t=0}^{T} \eta^{ev}\, p_{i,t}^{ev} \Delta t = E_i^{ev}, \quad \forall\ i. \tag{4}$$

$$\omega_{i,t}\underline{p}^{ev} \leq p_{i,t}^{ev} \leq \omega_{i,t}\overline{p}^{ev}, \quad \forall\ i, t. \tag{5}$$

For the battery, the net battery power $p_{i,t}^{b}$ is defined as the difference between the discharging power $p_{i,t}^{bd}$ and the charging power $p_{i,t}^{bc}$, as follows:

$$p_{i,t}^{b} = p_{i,t}^{bd} - p_{i,t}^{bc}, \quad \forall\ i, t. \tag{6}$$

The state of charge of the battery is represented by $e_{i,t}^{b}$, and the efficiency of charging and discharging are represented by η_c^b and η_d^b, respectively. $e_{i,t}^{b}$ is determined as follows:

$$e_{i,t}^{b} = e_{i,t-1}^{b} + \left(\eta_c^b p_{i,t}^{bc} - \frac{p_{i.t}^{bd}}{\eta_d^b}\right)\Delta t, \quad \forall\ i, t. \tag{7}$$

Charging and discharging power as well as batter state of charge are constrained by upper and lower limits.

Finally, every household has a connection to the microgrid, allowing for withdrawal and injection of real and reactive power. Net power injections into the microgrid are designated as $p_{i,t}$ and $q_{i,t}$ with positive values representing injection and negative values representing withdrawal. $p_{i,t}$ and $q_{i,t}$ are calculated as follows:

$$p_{i,t} = p^{g}_{i.t} + p^{pv}_{i.t} + p^{b}_{i.t} - p^{l}_{i.t} - p^{ev}_{i.t}, \quad \forall\ i,t. \tag{8}$$

$$q_{i,t} = q^{g}_{i.t} - q^{l}_{i.t}, \quad \forall\ i,t. \tag{9}$$

4.2.2.3 AC-OPF problem

For the complex power flow through line *i* at time t, $P_{i,t}$ and $Q_{i,t}$ represent the real and reactive power flow. The convention is adopted that positive values represent power flow from *i* to *j*. The squared voltage at node *i* is represented by $\nu_{i,t} = v^2_{i,t}$ and the squared current is represented by $\psi_{i,t} = I^2_{i,t}$. These quantities can be related by adopting the branch flow model for modelling the AC power flow in a single-phase radial network [41]. The branch flow model is then relaxed using a Second Order Cone (SOC) convex relaxation [41]. The following equations from the branch flow model are considered:

$$p_{i,t} = P_{i,t} - \textstyle\sum_{k\in\delta_i} P_{k,t} - r_i\psi_{i,t}, \quad \forall\ i,t. \tag{10a}$$

$$q_{i,t} = Q_{i,t} - \textstyle\sum_{k\in\delta_i} Q_{k,t} - x_i\psi_{i,t}, \quad \forall\ i,t. \tag{10b}$$

$$\nu_{i,t} = \nu_{j,t} + 2\left(r_i P_{i,t} + x_i Q_{i,t}\right) - \psi_{i,t}\left(r_i^2 + x_i^2\right), \quad \forall\ i,t. \tag{10c}$$

$$\psi_{i,t} = \frac{P^2_{i,t} + Q^2_{i,t}}{v_{i,t}}, \quad \forall\ i,t. \tag{10d}$$

Eq.(10d) is a non-convex constraint, and is relaxed to the following inequality [44]:

$$P^2_{i,t} + Q^2_{i,t} \le \psi_{i,t} v_{i,t}, \quad \forall\ i,t. \tag{11}$$

The squared voltage $v_{i,t}$ is to be constrained within upped and lower limits, which are defined as 5% above and below a nominally defined voltage.

The optimization objective of the AC-OPF problem is to minimize total costs of grid imports for every household. It is formulated as follows:

$$\begin{aligned} &\text{minimize.} \qquad \sum_{t=0}^{T}\sum_{i=0}^{N} C_{i,t}\left(p^{g}_{i,t}\right), \\ &\text{subject to Eqs. } (4) - (11). \end{aligned} \tag{12}$$

4.2.2.4 Trading mechanism

For the trading mechanism, the unified prosumer market proposed in [43] is adopted. The unified model provides options for implementing either a pool market model or a bilateral trading system. For the purposes of this study the bilateral trading form is used, which allows the designation of a bilateral trading coefficient to every individual trade. Bilateral trading coefficient values can be decided by the household owners and can thus be used to indicate preferred trading partners and enable product differentiation. Every node in is considered to be a separate rational, non-strategic market agent. In the unified prosumer market model, costs for every separate agent are minimized across their set of connected assets. This includes the costs of trading with the other participants. It is formulated as follows:

$$\text{minimize } \sum_{t=0}^{T}\sum_{i=0}^{N}\left[\sum_{a=1}^{\mathcal{A}} f_{i,t}^{a}\left(p_{i,t}^{a}\right) + \sum_{j=0}^{\mathcal{M}} \gamma_{ij,t}\left|d_{ij,t}\right|\right], \tag{13a}$$

$$\text{subject to} \quad \boldsymbol{D}_t = -\boldsymbol{D}_t^T \quad [\boldsymbol{\Xi}_t] \qquad \forall\, t, \tag{13b}$$

$$\sum_{a=1}^{\mathcal{A}} p_{i,t}^{a} = \sum_{j=0}^{\mathcal{M}} d_{ij,t}, \qquad \forall\, i,t, \tag{13c}$$

$$p_{i,t}^{a} \in \mathcal{P}_{i,t}^{a} \qquad \forall\, a,i. \tag{13d}$$

Here, $\mathcal{A}$ indexed by a represents the set of assets of agent i, and $\mathcal{M}$ indexed by j represents the set of trading partners of agent i. $f_{i,t}^{a}\left(p_{i,t}^{a}\right)$ represents the cost function of asset a as a function of the power setpoint $p_{i,t}^{a}$. $\gamma_{ij,t}$ represents the bilateral trading coefficient imposed by agent i on the trade between agents i and j, and $d_{ij,t}$ is the quantity of electricity traded between agents i and j. The matrix $\boldsymbol{D}$ contains the quantities of all trades, and the associated dual variable matrix $\boldsymbol{\Xi}$ contains the prices of all trades. The set $\mathcal{P}_{i,t}^{a}$ contains the feasible set of power set points of i at time t. Constraint Eq. (13b) enforces reciprocity of trade quantities, and reciprocity of trading prices is also implicitly enforced by this constraint as it is the dual variable. Constraint Eq. (13c) ensures that the sum of all power generated by agent i equals the sum of the quantities of all trades conducted.

4.2.2.5 Decentralized formulation

In order to optimize in a distributed manner, the general consensus optimization form of the Alternating Direction Method of Multipliers algorithm is used, based on the formulation from [45]. In its general form, it is written as follows:

$$\text{minimize.} \quad \sum_{i=0}^{\mathcal{N}} f_i(x_i), \quad \forall\, i, \tag{14a}$$

$$\text{subject to} \quad x_i - \widetilde{z}_i = 0 \qquad \forall\, i, \tag{14b}$$

From this, the augmented Lagrangian of this problem is formulated as follows:

$$L_{\rho(x,y,z)} = \sum_{i=0}^{\mathcal{N}}\left(f_i(x_i) + y_i^T(x_i - \widetilde{z}_i) + \frac{\rho}{2}(\|x_i - \widetilde{z}_i\|_2^2)\right), \tag{15}$$

where y represents the dual variable, and ρ represents the predefined penalty parameter (i.e. the step size). In Eq. (15), minimizing the second and third terms enforces constraint Eq. (14b). Eq. (15) is solved through a series of iterative steps, which are formulated as:

$$x_i^{k+1} = \underset{x_i}{\operatorname{argmin}}\left(f_i(x_i) + y_i^{k^T}\left(x_i - \widetilde{z}_i^{\,k}\right) + \frac{\rho}{2}\left(\left\|x_i - \widetilde{z}_i^{\,k}\right\|_2^2\right)\right), \tag{16a}$$

with

$$z_g^{k+1} = \frac{1}{k_g}\sum_{\mathcal{G}(i,c)=g}(x_i^{k+1})_c, \tag{16b}$$

$$y_i^{k+1} = y_i^k + \rho\left(x_i^{k+1} - \widetilde{z}_i^{\,k+1}\right), \tag{16c}$$

Eq. (16b) is essentially an averaging of all local variable components to retrieve the corresponding global variable component. The ADMM algorithm will iterate through the steps until the convergence conditions are met. These conditions are evaluated through the primal and dual residual values r^k and s^k, which are defined as follows:

$$r^k = x_i - \tilde{z}_i^{\,k} \tag{17a}$$

$$s^k = z_g^k - z_g^{k-1} \tag{17b}$$

with convergence conditions defined as:

$$\left\| r^k \right\|_2 \leq \epsilon_p \tag{18a}$$

$$\left\| s^k \right\|_2 \leq \epsilon_d \tag{18b}$$

In Eqs. (18a) and (18b), ϵ_p and ϵ_d are the allowed tolerances for the primal and dual residuals, respectively, which are typically assigned a low value in the range of 10^{-2} – 10^{-3}. Besides meeting the convergence conditions, the execution of an ADMM algorithm is also typically assigned a maximum number of iterations after which execution of the algorithm will end automatically.

The AC-OPF of Eq. (12) is reformulated using the general consensus form ADMM. The global optimization problem is decomposed into a set of subproblems where every node $i \in \mathcal{N}$ solves its own local subproblem using its own set of local variables x_i. In this set of local variables, the subset of local private variables $(x_i)_i := [p_i, p_i^g, q_i, q_i^g, \psi_i, p_i^b, p_i^{bc}, p_i^{dc}, e_i^b, p_i^{ev}]$ generally contains the variables pertaining to local energy infrastructure and the set of local coupling variables $(x_u)_i := [P_i, Q_i, v_i, P_{\delta(i)}, Q_{\delta(i)}, v_{\pi(i)}]$ generally contains the variables pertaining to its set of branch flow equations. The set of global variables is denoted as $z_g := [P, Q, v]$. Figure 7 shows how the locally calculated coupling variables correspond to the global variables in the present OPF problem. The steps of the ADMM algorithm are executed according to Eqs. (16a)–(16c), as follows:

$$\underset{p_{i,t}^g}{\operatorname{argmin}} \left(C_{i,t}\left(p_{i,t}^g\right) + y_i^{k^T}\left(x_i - \tilde{z}_i^{\,k}\right) + \frac{\rho}{2}\left(\left\| x_i - \tilde{z}_i^{\,k} \right\|_2^2 \right) \right), \tag{19}$$

Subject to Eqs. (4) – (11), with $z_g^{k+1}$and y_i^{k+1} as defined in Eqs. (16b) and (16c).

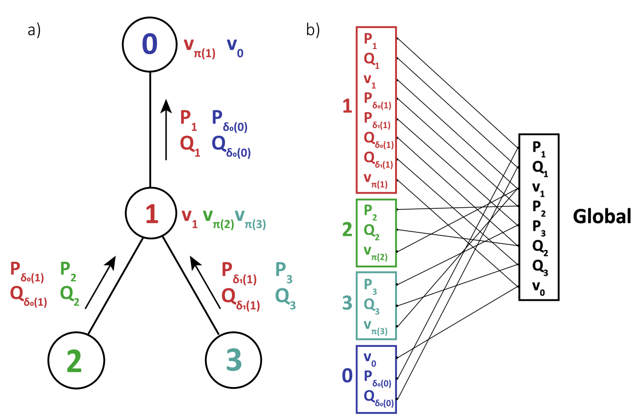


Figure 7 *–An illustration of the coupling between local and global variables in the ADMM-based general form consensus method for the OPF problem in a 4-nodes (0-3) network (as example) [31].*

For the OPF problem, the centralized optimization problem Eq. (13a) is decomposed into subproblems where every agent solves their corresponding subproblem. Every agent will determine their own local trading schedule $\boldsymbol{D}$, which is treated as a coupling variable that corresponds to the global variable $\boldsymbol{C}$.

Following [43], $(\boldsymbol{C}-\boldsymbol{C}^T)/2=\boldsymbol{D}$ is defined as the average of the trading quantity proposed by agent *i* to agent *j* and the trading quantity proposed by agent *j* to agent *i*. By using this consensus constraint, the fully decentralized augmented Lagrangian for bilateral trading can be formulated as follows:

$$\left(p_i^g, D_i\right)^{k+1} = \underset{p_i^g, D_i}{\operatorname{argmin}} \sum_{t=0}^{\mathcal{T}} \left[C_{i,t}^g\left(p_{i.t}^g\right) + \sum_{j=0}^{\mathcal{M}} \left[\gamma_{ij,t} \left| d_{ij,t}^{k+1} \right| + \frac{\phi}{2} \left(\frac{d_{ij,t}^k - d_{ji,t}^k}{2} - d_{ij,t}^{k+1} + \frac{\xi_{ij,t}^{k+1}}{\phi} \right)^2 \right] \right], \quad (20a)$$

$$\text{subject to} \quad p_{i,t} = \sum_{j=0}^{\mathcal{M}} d_{ij,t} \quad \text{and Eqs. } (4)-(8) \qquad (20b)$$

Here the penalty parameter is represented ϕ by to distinguish it from the penalty parameter ρ in Eq. (19). Dual variable ξ represents the price of trading and is updated as follows:

$$\xi_{ij,t}^{k+1} = \xi_{ij,t}^k - \frac{\rho}{2}\left(\frac{d_{ij,t}^k - d_{ji,t}^k}{2}\right), \qquad (21)$$

Finally, the combination of the OPF problem with a trading mechanism in a single distributed optimization problem leads to a fully decentralized algorithm that achieves maximum total social welfare by minimizing both grid import costs and trading costs for every agent $i \in \mathcal{N}$ separately and in parallel respecting global grid constraints and balancing supply and demand. The fully decentralized algorithm consists of several iterative steps. First, the local optimization problem is solved by agent *i*:

$$(x_i, D_i)^{k+1} = \underset{x_i, T_i}{\operatorname{argmin}} \sum_{t=0}^{\mathcal{T}} \left[C_{i,t}^g\left(p_{i.t}^g\right) + y_{i,t}^{k^T}\left(x_{i,t} - \widetilde{z_{\iota,t}}^k\right) + \frac{\rho}{2}\left(\left\|x_{i,t} - \widetilde{z_{\iota,t}}^k\right\|_2^2\right) + \right.$$
$$\left. \sum_{j=0}^{\mathcal{M}} \left[\gamma_{ij,t} \left| d_{ij,t}^{k+1} \right| + \frac{\phi}{2} \left(\frac{d_{ij,t}^k - d_{ji,t}^k}{2} - d_{ij,t}^{k+1} + \frac{\xi_{ij,t}^{k+1}}{\phi} \right)^2 \right] \right],$$

$$\text{subject to Eqs. } (4)-(11), (20b) \qquad (22)$$

Note, two separate penalty parameters are used, ρ for the grid constraints and ϕ for the trading mechanism. Since the only cost-generating asset in this setup is the external grid connection, $\sum_{a=1}^{\mathcal{A}} f_{i,t}^a\left(p_{i,t}^a\right)$ in Eq. (13a) is replaced by $C_{i,t}^g\left(p_{i.t}^g\right)$ being the cost function of the external grid connection. In the first step, agent *I* calculates not the set of local variables x_i and the optimal trading schedule $\boldsymbol{D}$ for every timestep. Then, in the next timestep, the global variables z_g are calculated:

$$z_g^{k+1} = \frac{1}{k_g} \sum_{\mathcal{G}(i,c)=g} \left(x_i^{k+1}\right)_c, \qquad (23)$$

Finally, in the third step, the dual variables ξ and y are updated by every agent:

$$\xi_{ij,t}^{k+1} = \xi_{ij,t}^k - \frac{\rho}{2}\left(\frac{d_{ij,t}^k - d_{ji,t}^k}{2}\right) \qquad \forall\, j, t, \qquad (24a)$$

$$y_i^{k+1} = y_i^k + \rho\left(x_i^{k+1} - \widetilde{z_\iota}^{k+1}\right). \qquad (24b)$$

After every iteration, separate residuals for grid constraints and trading are calculated as follows:

$$r_{grid}^{k+1} = \sum_{i=0}^{\mathcal{N}} x_i^k - \widetilde{z_\iota}^k, \qquad (25a)$$

$$s_{grid}^{k+1} = \sum_{i=0}^{\mathcal{N}} \widetilde{z_\iota}^k - \widetilde{z_\iota}^{k-1}, \qquad (25b)$$

$$r_{trade}^{k+1} = \sum_{i=0}^{\mathrm{N}} \sum_{t=0}^{\mathcal{T}} \sum_{j=0}^{\mathcal{M}} \left(d_{ij,t}^{k+1} + d_{ji,t}^{k+1}\right)^2, \tag{25c}$$

$$s_{trade}^{k+1} = \sum_{i=0}^{\mathrm{N}} \sum_{t=0}^{\mathcal{T}} \sum_{j=0}^{\mathcal{M}} \left(d_{ij,t}^{k+1} - d_{ij,t}^{k}\right)^2, \tag{25d}$$

4.2.2.6 Evaluations

The optimization of the algorithm performance was tested in terms of tractability (i.e., finding a global optimal solution) and efficiency (i.e., in terms of computational time. This we can ensure for a small network. The testing of the algorithms for bigger networks for future applications was not possible due to lack of data, and limited time, as developing the algorithm took longer than planned. As a result, we prioritized the finalization of the project for the community we had before starting with future projects.

We thus proceeded with the exploration of four scenarios that had not been planned originally: 1) baseline (no trading), 2) trade only, 3) grid only, and 4) combined trade and grid, see section 4.4.

4.3. WP3: Implementation on blockchain

4.3.1. Blockchain set-up

By adopting blockchain and smart contracts technology the developed distributed algorithm of section 4.2 can be executed in a secure, verifiable manner that ensures independence and anonymity of the market participants. In such a setup, the role of the smart contract is essential. A smart contract is a piece of computer code that is deployed on the blockchain and can execute certain functions when called upon by other nodes. The smart contract takes over the function of a central aggregator, thus effectively functioning as a virtual aggregator. In this role, the smart contract performs several types of functions: 1) executing parts of the ADMM algorithm, 2) exchanging information with other nodes, and 3) giving permission to other nodes to proceed with the next operation.

Various steps in the ADMM algorithm are distinguished where these functions are executed. Here we use the Solidity language [46] to write the smart contract. Other files that are run locally are written in Python, while Web3.py [47] is used to communicate between Python and the contract. The local optimization problems are solved using the Cvxpy package [48]. The blockchain network is set up by running a local Ethereum node with Ganache-cli [49]. Note, that this blockchain setup is not assessed for efficiency of communication, security, execution speed and energy consumption, as the purpose foremost to demonstrate its usability. See also section 4.4.6.

Upon setting up the blockchain network every node i is assigned a personal account with address λ, and the smart contract σ is assigned an account λ_σ. The contract is deployed to the network using a set of constructor variables $\theta := \left[n, \rho, \varphi, \varepsilon_p^g, \varepsilon_d^g, \varepsilon_p^t, \varepsilon_d^t, \mu\right]$ that configure the integrated ADMM algorithm. The variable μ represents the maximum number of iterations, and n represents the total number of nodes on the network. It is not required to pass any information on the network topology. As the contract is deployed, the bytecode of the contract's contents ABI_σ are generated. λ_σ and ABI_σ must be known by all other nodes to allow them to interact with the contract.

Figure 8 visualizes the necessary steps for execution of the ABMM algorithm on the blockchain network.

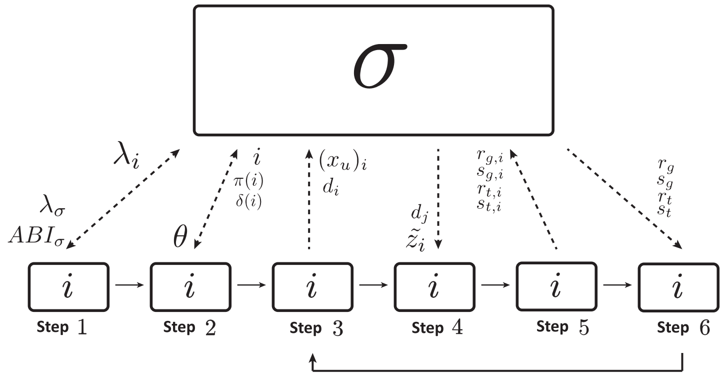


Figure 8 *– A flowchart showing the interaction between the smart contract σ and node i in the steps of the ADMM algorithm. The g and t subscripts indicate grid and trade residuals, respectively [31].*

Six steps can be discerned:

1. Starting step in which node i connects to smart contract σ by using the address λ and bytecode ABI_{σ}. This action only has to be performed once, for all nodes.
2. In this step a new round of optimization starts for the next day, and all nodes will declare their participation by passing i, the number of the node, and $\pi(i)$ and $\delta(i)$, the numbers of the parent and child nodes. Also, the nodes will retrieve θ from the contract to configure the local optimization problem. σ keeps track of participating nodes using a counter and when all n nodes have declared participation; the nodes will proceed to solve their local optimization problem.
3. When local optimization (Eq. (22)) is complete, the nodes send their sets of coupling variables $(x_u)_i$ and their set of trade bids d_i to the smart contract which will keep track using a counter. When all nodes submitted their coupling variables, one node is configured to call the z-update step function, which will make the contract execute Eq. (23) of ADMM. The set of trade bids contains the optimally calculated trading quantities for all trading partners and all timesteps. For the trading portion, the only role of the smart contract is to gather all trade bids and distribute them to the respective trading partners.
4. When the z-update step is complete, the nodes will retrieve the recalculated global variables $\widetilde{z_i}$ as well as the trade bids of their trading partners d_j. The nodes will form their full trading quantity matrix $d_{ij,t}$ and calculate their local penalty values as in Eq. (24a) and Eq. (24b). The nodes will also calculate the partial residual values as in Eqs. (25a)–(25d) for their local problem.
5. The nodes send the partial residuals $r_{grid,i}$, $s_{grid,i}$, $r_{trade,i}$, $s_{trade,i}$ to the contract, which initiates a counter and sums all partial residuals upon completion to receive the global residuals. The nodes periodically call checking functions to check for completion.
6. The nodes retrieve the global residual values r_{grid}, s_{grid}, r_{trade}, s_{trade} and evaluate the converge conditions. If the conditions are not satisfied, it goes back to step 3) and repeats the procedures until conditions are met.

If at any point in the algorithm a node fails to provide the necessary information, the system will timeout since full optimization needs all the information from every node to complete. It can be recognized that very little sensitive information is shared by the nodes with the contract. All information regarding the local energy infrastructure (i.e. local private variables $(x_l)_i$ remains private: only data on power flows in adjacent lines is shared, as well as residual values and trade bids. This information is stored on the smart contract, and not accessible by any other nodes on the network. Furthermore, it can be recognized that the full network topology is not explicitly stated anywhere. Every node must only know its parent and children. As for the end-user interaction with the blockchain network, the HEMS could perform virtually all of the required actions. In the configuration of the optimization problem and connection to the blockchain network, all communication with the network can be automated in the HEMS, requiring no knowledge of the blockchain's operation on the part of the end-user.

4.3.2. Evaluation of platform performance on case study

The above described procedures are tested using measured real power load and solar generation data from the East Harbour Prosumers Community [50] in Amsterdam, which is managed by partner Resourcefully. The fixed reactive power load $q^l_{i,t}$ is assumed to be proportional to $-0.1p^l_{i,t}$, with $p^l_{i,t}$ the fixed real power load. The topology is indicated in Fig. 9, based on [51]. In this microgrid 11 households are prosumers of which 3 also own an EV, and 11 households are consumers of which 5 own an EV. For grid electricity withdrawals, a time-of-use price signal t is used from the day-ahead market clearing prices of the European Power Exchange (EPEX) Netherlands [52]. Based on average daily distance travelled in the Netherlands by EV, the average EV daily charging demand (E_{ev}) is set at 7.06 kWh [53] (equivalent to about 36 km/day). The charging hours ω_i are pre-defined, with some households preferring to charge during the day and others during the night. The charging efficiency of an EV is set at 90%, and the battery efficiency is set at 95%.

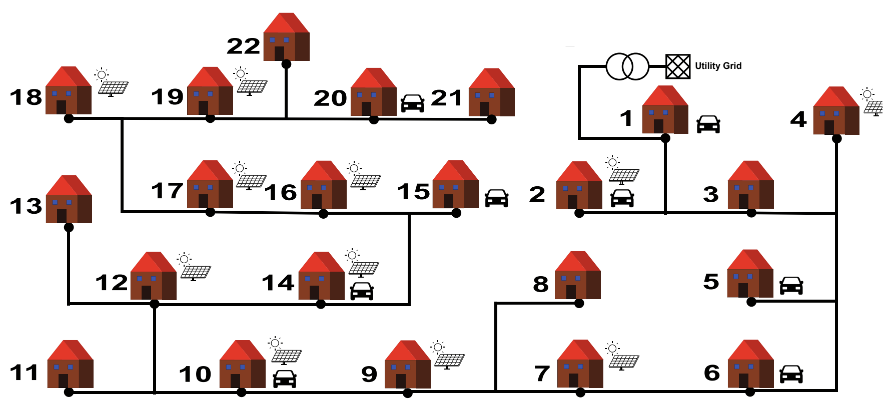


Figure 9 *– Topology of the considered microgrid. Owners of EV and PV are indicated. The utility grid is connected to the microgrid close to node 1 [31].*

For every day, the bilateral trading coefficients are pre-determined for every household based on their fixed real power consumption and solar PV generation data. It should be emphasized that in a real setup the values of the coefficients are decided by the household owners to indicate preferred trading partners or allow for product differentiation. It is assumed that the willingness to trade of a household i in any timestep t is proportional to the magnitude of their expected deficit/surplus $p^l_{i,t} - p^{pv}_{i,t}$. It is assumed that households with an expected surplus budget are more likely to trade with households that have an expected deficit and vice versa. In order to reflect these assumptions in the bilateral trading coefficients, several steps are taken.

First, the expected net budget matrix $\boldsymbol{P}^{net}$ is determined. Along the rows it contains all households and is indexed by i, and along the columns it contains all timesteps and is indexed by t. $\boldsymbol{P}^{net}$ is defined as

$$\boldsymbol{P}^{net} = \boldsymbol{P}^{pv} - \boldsymbol{P}^{l} \tag{26}$$

where $\boldsymbol{P}^{pv}$ and P^{l}have the same dimensions as $\boldsymbol{P}^{net}$. From matrix $\boldsymbol{P}^{net}$, two new matrices $\boldsymbol{P}^{buy}$ and $\boldsymbol{P}^{sell}$ are defined. These matrices contain the amount of power that each household wants to sell or buy in every timestep. The elements from these matrices are determined as follows:

$$p_{i,t}^{buy} = \begin{cases} 0 & \text{if} \quad p_{i,t}^{net} \geq 0 \\ p_{i,t}^{net} & \text{if} \quad p_{i,t}^{net} < 0 \end{cases} \tag{27a}$$

$$p_{i,t}^{sell} = \begin{cases} p_{i,t}^{net} & \text{if} \quad p_{i,t}^{net} > 0 \\ 0 & \text{if} \quad p_{i,t}^{net} \leq 0 \end{cases} \tag{27b}$$

From these matrices, two column vectors $\bar{P}_{max}^{buy}$ and $\bar{P}_{max}^{sell}$ are defined. Each element of these vectors represents the maximum value in the corresponding row of the matrices $\boldsymbol{P}^{buy}$ and $\boldsymbol{P}^{sell}$. This means that these vectors contain the maximum deficit and surplus budget of every household across all timesteps. $\boldsymbol{P}^{buy}$ and $\boldsymbol{P}^{sell}$ are then normalized as:

$$\boldsymbol{\Gamma}^{b,rel} = \frac{\chi}{2} \frac{\boldsymbol{P}^{buy}}{\bar{P}_{max}^{buy}} \tag{28a}$$

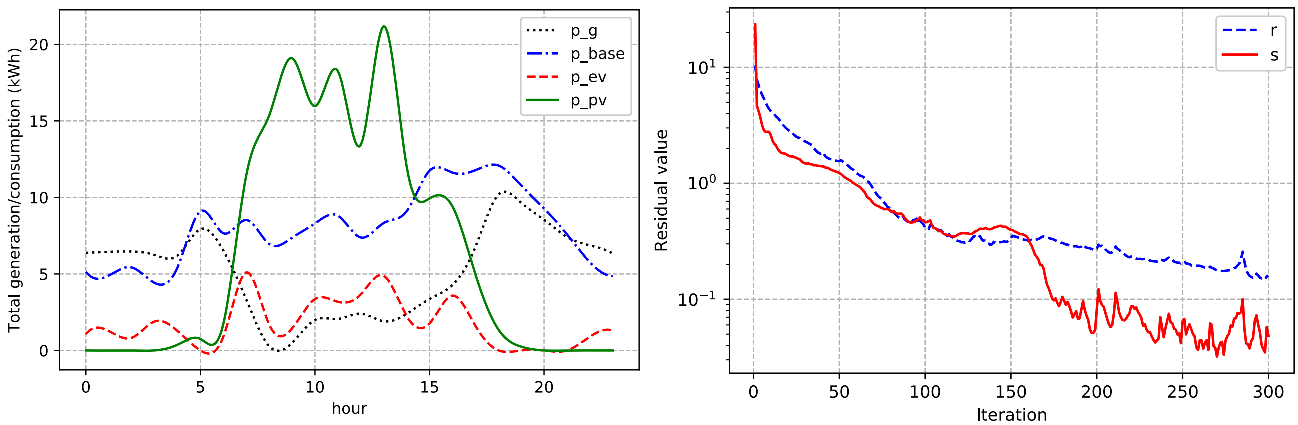
$$\boldsymbol{\Gamma}^{s,rel} = \frac{\chi}{2} \frac{\boldsymbol{P}^{sell}}{\bar{P}_{max}^{sell}} \tag{28b}$$

Matrices $\boldsymbol{\Gamma}^{b,rel}$ and $\boldsymbol{\Gamma}^{s,rel}$ represent the relative willingness of households to buy or sell electricity. Parameter χ represents the maximum, baseline value for bilateral trading coefficients. From matrices $\boldsymbol{\Gamma}^{b,rel}$ and $\boldsymbol{\Gamma}^{s,rel}$, the final 3D matrix of bilateral trading coefficients $\boldsymbol{\Gamma}$ is defined as follows:

$$\gamma_{ij,t} = \begin{cases} \chi & \text{if} \quad \gamma_{i,t}^{s,rel}, \gamma_{j,t}^{s,rel} > 0 \\ \chi & \text{if} \quad \gamma_{i,t}^{b,rel}, \gamma_{j,t}^{b,rel} > 0 \\ \chi - \left(\gamma_{i,t}^{b,rel} + \gamma_{j,t}^{b,rel} + \gamma_{i,t}^{s,rel} + \gamma_{j,t}^{s,rel}\right) & \text{otherwise} \end{cases} \tag{29}$$

At the maximum value of $\gamma_{ij,t} = \chi$, nodes i and j are considered very unlikely trading partners. In this work we take $\chi = 10$, meaning that all bilateral trading coefficients have a value of anywhere between 0 and 10.

As a first functional test, generation and consumption data of 21 June 2018 are used. The total generation schedule of the feeder 0 (grid connection) and the scheduling of EV charging for all households are visualized in Fig. 10a, as well as the total PV generation and the total base load. It can be seen that the thermal generator is most active during the peak hours in early morning and early evening, when there is no solar generation and load is relatively high. It can also be seen that EV charging is lowest during these times and is instead scheduled during the day and night. The convergence of the algorithm is shown in Fig. 10b. The algorithm is run for 300 iterations, at which point the total costs are 0.8 percent higher than in a centralized solution.



(a) (b)

***Figure 10** – (a) Total electricity generation and consumption schedule of all households on 21 June 2018, (b) Convergence of the ADMM algorithm [32].*

4.4. WP4: Platform assessment

In order to evaluate the impact of including the bilateral trading mechanism and grid constraints on social welfare and scheduling of power flows and bilateral trades, several scenarios are compared where these different parts of the model are included and excluded. A baseline scenario will also be analyzed, where there is no microgrid and households only interact with the external grid. In all scenarios, prosumers are able to feed their excess electricity budget into the grid for 50% of the electricity price at that time. The scenarios are run for one week in summer (21–28 June 2018) and one week in winter (21–28 December 2018) to evaluate performance in both seasons. The various scenarios are shown in Table 3. The trade-only scenarios execute the optimization problem as in Eq. (20b), grid-only scenarios execute as in Eqs. (19a)–(19c), the combined scenarios execute as in Eq. (22). In the grid-only scenarios, there is no cost on the exchange of energy so that the impact of including the bilateral trading mechanism can be more clearly assessed in isolation. The objective of this study is to assess the performance of the integrated model and to compare it with a baseline scenario. This performance is assessed with regard to economic indicators and the scheduling of power flows. The economic performance is discussed in section 4.4.1 and the technical analysis in section 4.4.2.

***Table 3** – Scenarios tested.*

Scenario	Abbreviation	Scenario	Abbreviation
Baseline, summer	BS	Grid only, summer	GS
Baseline, winter	BW	Grid only, winter	GW
Trade only, summer	TS	Grid + trade, summer	TGS
Trade only, winter	TW	Grid + trade, winter	TGW

4.4.1. Economic assessment

The economic performance parameters represent financial costs for the households. Table 4 shows values for total social welfare across the entire week. Here a comparison is made between total prosumer costs and total consumer costs. Furthermore, Fig. 11 shows the price of electricity throughout the entire week, both for trading, grid imports and grid feed-in.

***Table 4** – Numerical results for economic indicators. All costs are summed over the entire summer or winter week and over all households. Prosumer and consumer costs are summed over all prosumer and consumer households, respectively. Relative costs are compared to the baseline scenarios, the values of which are set at 100%. For the trade costs, the values of the trade-only scenarios are set at 100%.*

	Summer				Winter			
Scenario	BS	GS	TS	TGS	BW	GW	TW	TGW
Prosumer import costs (Eur)	90.17	53.46	70.84	60.06	150.82	126.56	132.76	136.05
Consumer import costs (Eur)	92.23	30.01	59.59	58.74	151.44	118.19	148.02	147.32
Prosumer trade costs (Eur)	–	–	− 37.40	− 49.37	–	–	0	0
Consumer trade costs (Eur)	–	–	37.40	49.37	–	–	0	0
Total prosumer costs (Eur)	90.17	53.46	33.44	10.69	150.82	126.56	132.76	136.05
Total consumer costs (Eur)	92.23	30.01	96.99	108.11	151.44	118.19	148.02	147.32
Total import costs (Eur)	182.40	83.47	130.43	118.8	302.26	244.75	280.78	283.37
Total trade costs (Eur)	–	–	37.40	49.37	–	–	0	0
Total costs (Eur)	182.40	83.47	167.83	168.17	302.26	244.75	280.78	283.37
Relative prosumer import costs	100%	59.3%	78.6%	66.6%	100%	83.9%	88.0%	90.2%
Relative consumer import costs	100%	32.5%	64.6%	63.7%	100%	78.0%	97.7%	92.2%
Relative prosumer trade costs	–	–	100%	132.0%	–	–	100%	100%
Relative consumer trade costs	–	–	100%	132.0%	–	–	100%	100%
Relative total prosumer costs	100%	59.3%	36.8%	11.8%	100%	83.9%	88.0%	90.2%
Relative total consumer costs	100%	32.5%	105.2%	117.2%	100%	78.0%	97.7%	92.2%
Relative total import costs	100%	45.8%	71.5%	65.1%	100%	80.1%	92.9%	93.8%
Relative total trade costs	–	–	100%	132.0%	–	–	100%	100%
Relative total costs	100%	45.8%	92.0%	92.2%	100%	80.1%	92.9%	93.8%

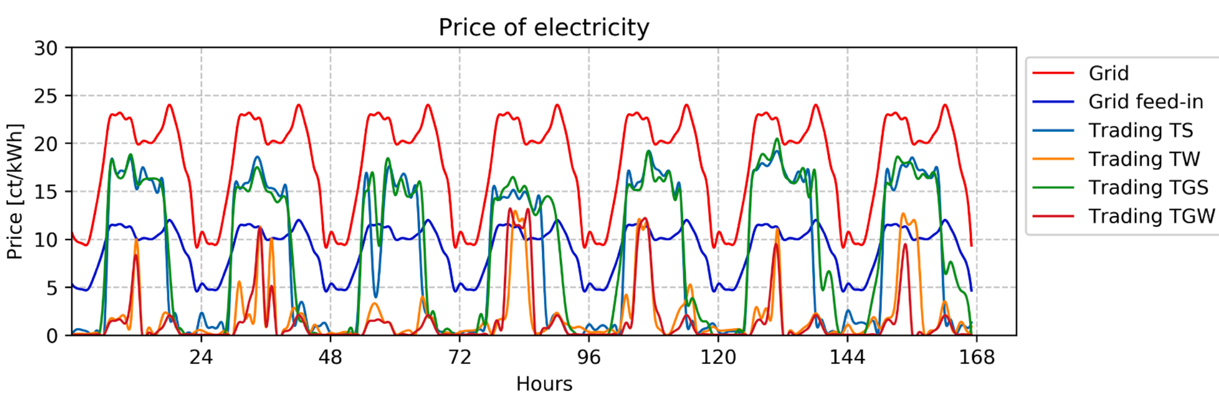


***Figure 11** – The price of electricity in the different scenarios [31].*

Looking at the results for total community-wide costs in Table 4, it can be recognized that in summer the baseline scenario yields the highest costs at 182 euros (note, we will used rounded numbers). The GS scenario results in the lowest costs at around 83 euros, which is 45% of the baseline scenario. Total costs in the TS and TGS scenarios are only slightly lower than BS at around 168 euros, respectively. When regarding only external grid imports, which includes compensation from feed-in, the GS scenario is still the cheapest at 83 euros, but the difference between the BS scenario on the one hand and the TS and TGS scenarios on the other is much larger, with the BS coming in at 182 euros and the TS and TGS yielding 130 and 118 euros, respectively. Differences between the scenarios are larger when distinguishing prosumers and consumers. In the BS scenario, prosumer costs are almost the same as consumer costs around 90 euros. In the GS scenario, prosumer costs are 54 euros, which is higher than consumer costs at 30 euros. In both trading scenarios however, the difference between prosumers and consumers is much larger, with the total consumer costs being around 3 times higher than the prosumer costs in the TS scenario, and almost 10 times higher in the TGS scenario.

In the winter scenarios, differences between the scenarios are much smaller, but corroborate the same overall picture. Looking at Fig. 11, it can be recognized that during daytime hours, when trading is most likely to take place, the average internal trading price is lower than the price of grid imports yet higher than the compensation for grid feed-in. It can also be recognized that the TS and TGS scenarios yield similar results for the price of internal trading, as well as the TW and TGW scenarios. For the TG and TGW scenarios, the trading price is not between feed-in and withdrawal prices, but these data should not be considered meaningful or reliable since there is next to no trading happening in these scenarios.

The boxplots in Fig. 12 show the distribution of total costs data for households in every scenario, split up for prosumers (p) and consumers (c). It can be seen that in the GS scenario there is the least variation, both for consumer and prosumer households. In the trading scenarios, the variation is significantly larger, with the variation in TS being somewhat larger than in TGS.

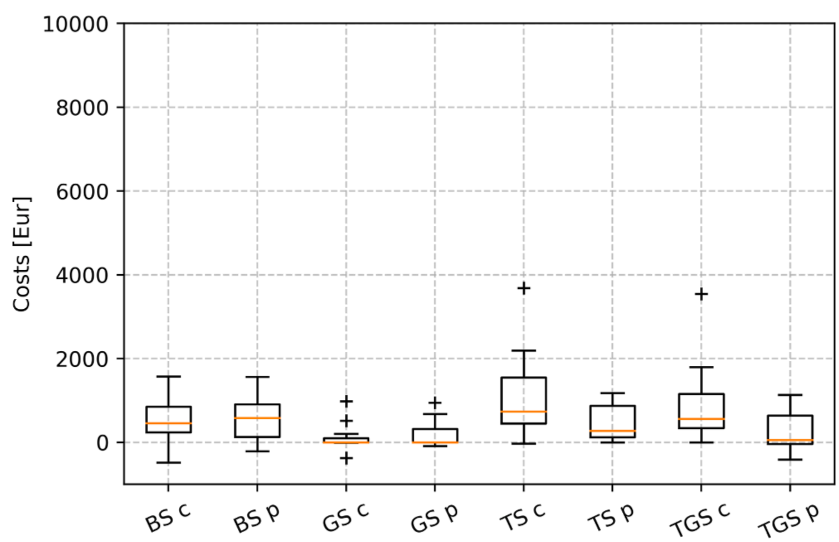


Figure 12 *– Boxplot showing the total costs for households in all scenarios. These data are summed over the entire week. The 'c' and 'p' indicate data for consumer and prosumer households, respectively. Yellow lines indicate median values of the particular group. [31].*

4.4.2. Technical assessment

Table 5 shows the results for energy imports and energy exchanged in all scenarios, in total and at peak hours. The GS scenario yields the highest local energy exchange at 495 kWh as there is no price on trading. The TGS scenario yields a similar amount at 468 kWh, with the TS being the lowest at 291 kWh of traded energy. For the winter scenarios, very little exchange is occurring as there is almost no excess solar electricity. For energy imports, the BS scenario shows a higher result than the other summer scenarios at a total withdrawal of 999 kWh. The GS scenario has the lowest consumption at 788 kWh, and the TS and TGS scenarios show values of 895 and 856 kWh, respectively. There is a large difference in peak imports, with the TS and BS scenario showing values of 70% of total imports, whereas in the GS and TGS scenarios the peak imports are around 35% of the total. In the winter scenarios again differences are smaller, there is only a noticeable variation with the peak imports where again GW and TGW scenarios yield the lowest values.

Table 5 *– Numerical results for energy consumption. Grid imports and the energy exchanged are summed over the entire week and over all households. Peak hours are defined as 6–9AM in the morning and 5–8PM in the evening, and peak imports are summed over all peak hours for all days and all households. Relative values are compared to the baseline scenarios, the values of which are set at 100%.*

	Summer				Winter			
Scenario	BS	GS	TS	TGS	BW	GW	TW	TGW
Total local energy exchange (kWh)	–	495	291	468	–	52	5	17
Total imports (kWh)	999	788	895	856	2638	2333	2530	2455
Peak imports (kWh)	731	273	620	302	1199	843	1140	876
Ratio of peak/total imports	0.73	0.34	0.69	0.35	0.45	0.36	0.45	0.35

Looking at Fig. 13, which shows the power exchanged throughout the first day of the four summer scenarios, it can be recognized that there is no import peak at peak hours in the GS and TGS scenarios. Furthermore, it appears that power flows are smoother and more consistent throughout the day. In the scenarios that include trading, this trading is limited during daytime hours when there is an excess of PV. In the GS scenario, there is some more exchange happening during other hours as well as it is free.

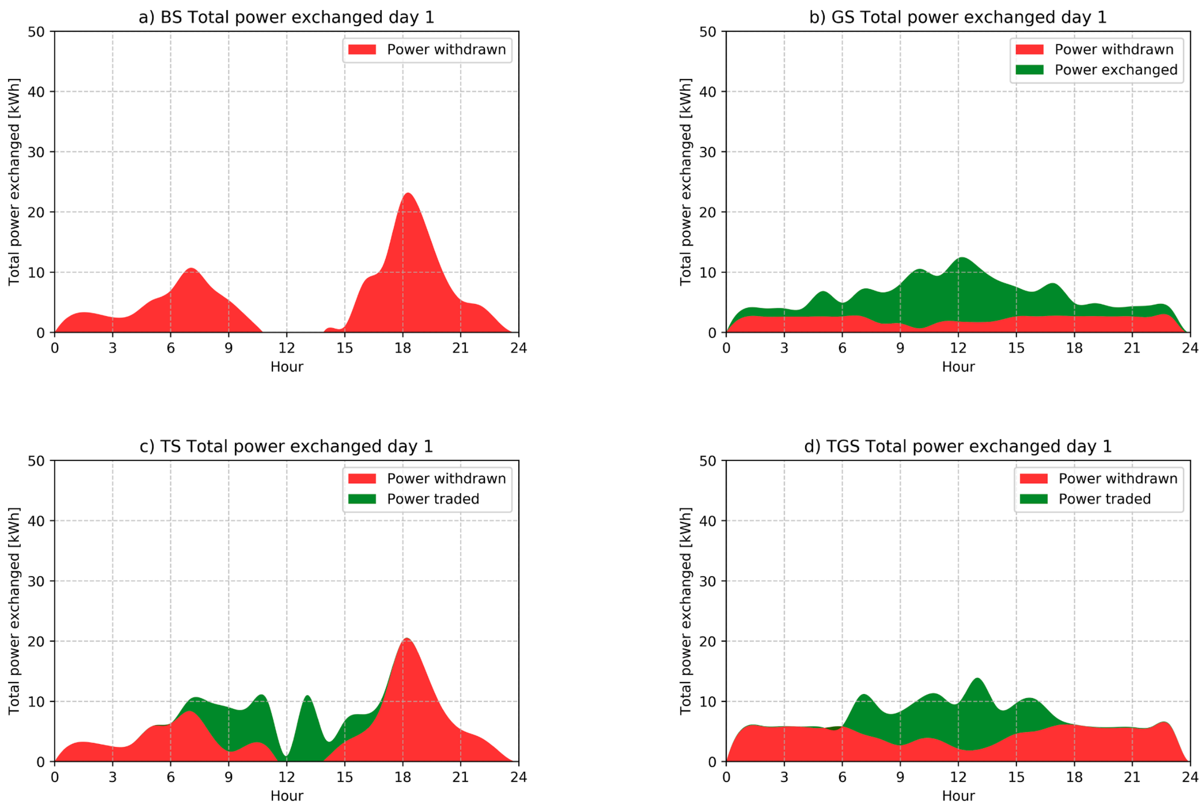


Figure 13 *– Power exchanged in all nodes during the first day of the four summer scenarios. Magnitudes are summed over all nodes [31].*

4.4.3. Evaluation of results

Based on the results shown in the figures and tables, a comparison can be made between the different scenarios for every performance category. We thus can discuss the respective benefits and downsides of the scenarios as well as their applicability in real-life communities.

We found that results in winter are very similar for all scenarios. This makes sense as there is very little excess PV electricity during this time of year, which means that the microgrid is relatively inactive as most PV electricity is self-consumed directly. Therefore, further discussion of the results will focus on the results of the summer scenarios only.

Out of the GS, TS and TGS scenarios, the GS scenario shows the most favourable results for total social welfare. Total costs in this scenario are considerably lower than for the other scenarios, which means that total social welfare is the highest. This can simply be explained by the absence of trading costs as energy is exchanged for free. GS scenario is also cheapest when considering only import costs however, and so it appears that the absence of a trading mechanism allows the microgrid to function at maximum efficiency.

When comparing TS and TGS scenarios, the inclusion of the microgrid constraints in TGS results in slightly higher import costs than in TS. This can be explained by efficiency losses which are not considered in the TS scenario. Although the total energy imports in Table 5 are compable for the three scenarios, the real difference shows in the peak imports, where the GS and TGS show peak imports that are less than half that of the TS and BS scenarios. It appears that inclusion of physical network constraints in the optimization problem means that the algorithm will avoid using the grid excessively during peak hours, not just because of cost incentives, but also because of possible congestion issues. From Fig. 13, it can be seen that overall power flows are smoother in the GS scenarios. In the TS and BS scenarios, this management is left to the DSO. Furthermore, when comparing the amount of energy that is traded in the TS and TGS scenarios, it appears that the TGS scenario allows for a larger quantity of energy to be traded at a similar price as the TS scenario. Possibly this is a result of more local trading during peak hours to compensate for the lower external grid imports.

Looking at the differences between total prosumer and consumer costs, the inequality is significantly larger in the trading scenarios than in the others. This makes sense given that this difference is primarily a result of the trading. When considering only import costs, it appears that consumers benefit more than prosumers from the proposed setup as compared to the BS scenario. Still, it is clear that owners of PV benefit of their investment through the trading. The GS scenario is most beneficial for consumers, yet prosumers still benefit as compared to the TS and TGS scenarios. When comparing the TS and TGS scenarios the figures are similar. Prosumers benefit more in the TGS scenario because of increased trading, and for the same reason consumers pay a bit more. This increased benefit is not a result of the trading price, which is similar in both scenarios as can be recognized from Fig. 11, but it is due to increased trading volume, as can be seen in Table 5. Figure 12 shows the spread in costs for all households. Similar to the other results, the GS scenario shows the lowest spread and the TS and TGS show a larger, yet similar spread. TGS spread appears to be somewhat smaller. In the winter scenarios the difference between consumers and prosumers is much smaller as there is very little trading happening.

4.4.4. Lessons learnt

We start with the notion that the baseline scenario represents a situation that is similar to the present situation in the distribution grid in many countries. There is no cooperation between households on any level, and prosumers may dispose of their excess PV-generated electricity by feeding it into the grid. A financial compensation is offered to them in the form of feed-in-tariffs (FiTs), and battery storage systems are only for private use. Consumers are completely reliant on their energy service providers to provide them with energy. Also, this scenario requires the DSO to monitor and distribute energy in the grid and ensure that all physical constraints are respected. Given the expected increase in DER adoption, this task will become more and more complex. Furthermore, considering the abolishment of net metering (in the Netherlands), prosumers must find other ways to optimally benefit from their installed PV systems.

We expect that the system configuration represented in the baseline scenarios will increasingly be replaced by alternative systems. This is supported by the result from this study that the BS scenario yields the highest total costs and grid imports of all summer scenarios. Of the other scenarios, the GS scenario yields the highest social welfare and lowest peak imports. In fact, peak imports are just over one-third of the BS scenario. This can be very beneficial for the DSO. This scenario can be conceptualized as a microgrid community that shares energy between community members. The GS scenario appears to only be viable when costs of grid imports are fairly shared across all members of the network or when the exchange of power is valued using for instance locational marginal prices, like in [54]. Furthermore, a way should be found to compensate investors of PV and batteries for their extra contribution to the total welfare of the community. This would require intensive cooperation between all participants on the network, and the resulting community would be akin to an energy collective. In such a community, there would be no need for a trading mechanism since all households will act in the interest of the group.

However, when intensive cooperation is not possible and households act in a mostly self-interested manner, the inclusion of a trading mechanism can regulate cooperation whilst still ensuring maximization of total social welfare. The TS scenario seems viable when all participants on the network are primarily self-interested and little cooperation between them is possible or desirable. Such a network may be akin to a full P2P market as discussed. The mechanism allows prosumers to maximally benefit from their PV and battery systems. The TGS scenario is similar to the TS scenario, except that grid management is adopted by the network participants. The largest benefit of this is a significant decrease in peak imports of over 50%. This can be very beneficial for the DSO. Furthermore, some efficiency losses from grid management are not included in the TS scenario because they are left to the DSO, meaning that in reality the energy consumption will be somewhat higher than the figures found here. It is also interesting that the inclusion of the OPF equations allows for more trading to take place in the TGS scenario, allowing participants to benefit more from the bilateral trading system that is in place. Monetarily speaking, prosumers do benefit more from TGS scenario as compared to consumers. As such, it is more heavily incentivized in the TGS scenario to have a PV installation than in the TS scenario.

Summarizing, for social welfare, it appears that the best result is achieved without implementing a trading mechanism (GS scenario), and a combination of physical microgrid constraints and trading mechanism (TGS scenario) yields lowest social welfare. However, not implementing a trading system means that intensive cooperation between the households is required, and that participants cannot benefit from the options and freedom provided by the bilateral trading mechanism. Furthermore, the trading mechanism favours owners of PV, incentivizing adoption and investment of such rooftop systems. When considering the TS and TGS scenarios, social welfare results are similar, and the main benefit from the addition of the OPF problem appears to be strongly reduced peak imports, as well as a slightly reduced total imports. Increased trading volume in TGS is also beneficial. Comparing to the baseline scenario, the other three scenarios show considerable benefits, especially regarding the import costs. Trading costs are spent by individual households, but the money remains within the community, thus arguable still benefiting the community as a whole. The TGS scenario shows lower import costs than the TS scenario at 35.4% lower than the baseline scenario, and peak imports are 60% lower than the baseline. Total imports are around 15% lower than in the baseline. Overall, it seems that applicability of the different scenarios in real life is dependent on the nature of the cooperation between the participants, as well as the cooperation between the community and the DSO.

Given that the present study proposes a platform that is implemented on blockchain, it seems reasonable that adopters of such platforms hold independence, free choice and anonymity in high regard, which could make it feasible for them to adopt any of the platforms modelled in the different scenarios. A platform similar to the GS scenario would fit a situation where independence and welfare of the community as a whole are deemed important. In this case, individuals must be prepared to collaborate intensively to fairly share costs and take responsibility for microgrid management. The TS scenario seems to fit a community where participants prioritize individual choice, freedom and welfare and do no desire to be involved in local grid management. The TGS scenario represents a middle ground where extra responsibility is adopted for management of the microgrid, but where cooperation between participants is regulated by a trading mechanism.

Finally, it should be emphasized that the proposed model is intended to function on a private blockchain network, where all participants are known and accepted members of the community. In this case, it is not possible for just anyone to enter the network and participate. Particularly when the platform is implemented in a microgrid environment this is impossible since it would require that the new participant is physically connected to the microgrid: in a trade-only scenario, it would be possible to allow new participants as no physical connection is required, although this might have consequences for overall performance of the algorithm when the number of participants becomes too large. Regarding end-user interaction with the network, virtually none is required: almost all actions can be automated by the HEMS, where the local optimization problem and communication with the blockchain network are all performed by the HEMS. The only input that the end-user would need to pass to the HEMS would be the designated EV charging hours. The bilateral trading coefficients could either be determined manually by the end user, or, like shown in this study, automatically calculated.

4.4.5. Limitations

First of all, the modelled platform is intended to function as a day-ahead optimization platform, meaning that outcomes are dependent on accuracy of PV generation and consumption forecasts. Regarding the implementation on blockchain, the suggested configuration has not been extensively tested for communication efficiency, security and execution speed, even though these are important factors. The aim of this study has been to provide a general framework for implementation and for using the smart contract. Regarding the development of the model, there are always inherent uncertainties in the software that is used, in this case Python, Cvxpy, Ganache-cli and Web3.py. Also, uncertainties are inherently present in the branch flow model and the ADMM algorithm, since a distributed optimization algorithm typically does not converge to exactly the same solution as a centralized algorithm. Furthermore, the proposed integrated model could benefit from a comprehensive sensitivity analysis to evaluate how the input parameters and setup of the two parts of the model affect performance and results in both categories.

Other important limitations arise from the assumptions that are made in the setup of the model. It has been assumed that all EVs have the same average charging demand and charging hours every day, which is not likely to occur in a real-life situation. Also, values have been assumed for the battery parameters, and assumptions have been made regarding the availability of reactive power generation and the topology of the grid. It is unclear whether varying the amount or distribution of DERs in the microgrid will severely affect the outcome, and the investment costs of the various assets has not been taken into account. For battery systems in particular, the investment costs can play a large role when making financial calculations in a model. Finally, the bilateral trading coefficients may have large impacts on the outcomes of the model. In this study, an effort has been made to set realistic values for the bilateral trading coefficients in a relatively straightforward manner based on the net power consumption in each timestep, but a more extensive modelling of prosumer market behaviour may provide further insights into the impact of the coefficient values.

4.4.6. Platform choice

In the above work we have used Ethereum as an initial Blockchain platform for testing purposes, while we selected IBM Hyperledger Fabric (HLF) as the best option blockchain platform for the actual implementation of the algorithms and models. It is known that Ethereum is not efficient (due to its heavy consensus mechanism) as it is a public platform and consumes a lot of energy. But it sufficed for our initial testing purposes. The setup of the HLF platform, as a permissioned blockchain platform supported by smart contracts, was only finalized towards the end of the project, and we could therefore perform limited tests only. Nevertheless, we found that changing the blockchain technical platform did not affect the P2P energy and optimization results that are described in this report, but performance was much better for the considered application: it has a unique architecture with a relatively energy-efficient consensus protocol that provides fast transaction speed with high security and reliability. One of its main characteristics is that it is a permissioned private blockchain which, for decentralized P2P energy trading applications, appears as an advantage since it is necessary to know the information of the peers (i.e., nodes) participating in the energy trading system. The HLF provides smart contract support in the form of Chaincode that can be written using the most popular programming languages (i.e., Go, Java or NodeJS). We thus recommend using Hyperledger Fabric for future implementation.

For larger networks with P2P energy trading between nodes that belong to multiple energy communities or neighborhoods, the blockchain implementation needs to be tested for efficiency of communication and execution speed. On the other hand, the HLF enables to change the block creation configuration in the runtime, therefore adapting the speed of transactions depending on the situation within the system. In such bigger networks, the security and smart contract vulnerabilities also become very important to consider.

5. Follow up activities

The B-DER project has managed to realize a P2P trading scheme implemented on a blockchain platform. It has produced unique results for UU, ECF and Resourcefully. The groundwork has been done and project results can be widely implemented.

UU will use the insights gained in several projects that are focusing on electricity market changes due to inclusion of prosumers and peer-to-peer trading, linking up with the H2020 project PVProsumers4Grid, the EFRO project SmartSolarCharging and the TKI-UE project Flexible Net Tariffs, with DSO Stedin and local Utrecht stakeholders. New project proposals have also been submitted for national funding, while preparatory work for submission of H2020 GreenDeal proposals has started . The obtained results will also be implemented in courses for master students at UU.

ECF will use the learned lessons from the B-DER-project as inputs for further exploration of practical blockchain implementations on the way to a climate neutral and a resilience society. Bringing this novel technology to fulfill its promise in all facets for society and more efficient administration of exchange information, trade, and markets in general, starting with the emerging markets related to climate and other sustainability public markets where information and data are values in itself. Making intangibles count is hard enough; doing it using innovative technology is making it more challenging. Participating in projects like a Master year Sustainable Financing and Entrepreneurship at the Hanze University in Groningen, to the practicalities of a "The Donut Economy" in Amsterdam. The B-DER project showed us what is needed to satisfy future demand. ECF has started a new development phase of its blockchain-based platform towards a more generic offering for other projects to build on.

And we will work together with Elena Georgarakis (Copernicus Institute University Utrecht) as a co-author of the paper she writes together with dr. Tarek Alskaif and (potentially) her other supervisor from Leipzig University. She wrote her master thesis within the B-DER project on "Energy exchange between households. What are the preferences for exchanging locally generated renewable energy in the Netherlands?" To that she intends to add the current state of policies and policy recommendations.

Resourcefully is taking advantage of the learnings from B-DER to further its engagement with the community in the Eastern Docklands area in Amsterdam, working together with UU staff and students as well as stakeholders such as the Municipality of Amsterdam, the local Energy Commission, sister-foundation Amsterdam Energy City Lab and infrastructure stakeholders such as DSO Liander and Waternet, with the aim to develop the local area into a living lab for smart energy technologies and achieve a high proportion of renewables integration. The knowledge is also applied in the energy transition consulting work of Resourcefully with Dutch local governments investigating the opportunities and potential for applying smart energy systems as part of their district rezoning, renovation and rebuilding activities to meet their transition goals and tackle electrification challenges.

6. Discussion, conclusion and recommendations

B-DER was an ambitious project with innovative and challenging objectives. All of these have been achieved and all experiences and results have led to further insights for all partners.

This project has shown how modelling of an integrated blockchain-based energy management platform that respects physical microgrid constraints and implements a bilateral trading mechanism can be done. The procedure of integrating the physical, economic and information layers in a single model has been shown in Section 2.

As a first main contribution, the formulation of a distributed optimization problem that respects physical microgrid limitations through OPF and a bilateral trading mechanism have been developed. As a second main contribution, the implementation of the distributed algorithm on a blockchain network has been specified. A smart contract can take on the role of virtual aggregator: not only does it have to execute the consensus step from the ADMM algorithm, it also functions as a central agent for distributing required information and data to all other nodes. Several scenarios are defined for comparison of economical and physical assessments.

The main findings are that although combining the trading mechanism and physical constraints yields a somewhat lower total social welfare, peak imports as well as grid import costs are reduced as compared to the trade-only scenario. The grid-only scenario, while showing the best results for social welfare, seems difficult to realize since intensive cooperation is required. Furthermore, it does not provide the benefits conferred by the bilateral trading mechanism. As such, it appears that there are considerable benefits to combining trading with physical constraints when designing energy optimization platforms, especially when comparing to the baseline scenario: import costs are reduced by 34.9%, and peak import quantity is reduced by 60%.

Regarding real-life applicability, it is argued that a trade-only scenario could represent full P2P type markets, whereas a grid-only scenario could represent an energy collective. The combined scenario could represent a middle ground where several downsides of the other scenarios are mitigated. Research into the social acceptance of the different scenarios and actual wishes of participants should give further insights into the practical feasibility.

The usefulness of the proposed model can be expanded in several ways. First of all, the model could be implemented on a live blockchain network to evaluate security, efficiency and execution speed in a real-life situation, where we recommend using the Hyperledger Fabric platform. Furthermore, the sensitivity of modelling results to input parameters such as trading coefficients, investment costs and DER distribution should be explored. Also, a detailed techno-economic assessment could be carried out to evaluate social welfare over an extended period of time.

7. Project implementation

The project has had various challenges listed in section 2, i.e. development of optimal power flow and trading algorithms as well as implementation on a blockchain platform. In the kick-off meeting with all partners it was agreed to schedule monthly meetings between key persons executing the work, with many bilateral meetings when needed. The project also benefitted a lot from the MSc thesis work of Gijs van Leeuwen; his work proved to be very fruitful.

The work progressed more or less in line with the schedule in the proposal. We have reached all objectives and have presented the work to the international scientific community as well as nationally.

8. Dissemination

Dissemination activities have aimed to promote non-confidential results obtained within the project as swiftly and effectively as possible for the benefit of the whole (scientific) community and to avoid duplication of R&D efforts.

Published papers

Tarek AlSkaif, Bart Holthuizen, Wouter Schram, Ioannis Lampropoulos, Wilfried van Sark, A Blockchain-based Configuration for Balancing the Electricity Grid with Distributed Assets, World Electric Vehicle Journal 12 (2020) 62 (doi:10.3390/wevj11040062)

Gijs van Leeuwen, Tarek AlSkaif, Madeleine Gibescu, Wilfried van Sark, An integrated blockchain-based energy management platform with bilateral trading for microgrid communities, Applied Energy 263 (2020) 114613. (doi:10.1016/j.apenergy.2020.114613)

I. Lampropoulos, T. Alskaif, W. Schram, E. Bontekoe, S. Coccato, W. van Sark, Review of energy in the built environment, Smart Cities 2020, 3, 248–287. (doi:10.3390/smartcities3020015)

Jose L. Crespo-Vazquez, Tarek AlSkaif, Ángel M. González-Rueda, Madeleine Gibescu, A Community-Based Energy Market Design Using Decentralized Decision-Making under Uncertainty, IEEE Transactions on Smart Grids (2020). (Accepted, in Press)

Conference contributions

Hugo Schönbeck, The regulatory framework, Blockchain2Energy conference, 13 February 2019, Amsterdam, the Netherlands, (https://europe.blockchain2energy.com/program/?utm_source=solarplaza&utm_medium=email&utm_campaign=last-call-updates)

Tarek AlSkaif, Gijs van Leeuwen, Decentralized Optimal Power Flow in Distribution Networks Using Blockchain, 2nd International Conference on Smart Energy Systems and Technologies, SEST-2019, 9-11 September 2019, Porto, Portugal. (doi:10.1109/SEST.2019.8849153)

Hugo Schönbeck, Tarek AlSkaif, Wilfried van Sark, Hugo Niesing, Avi Ganesan, Anne-Marie Pronk, Brian Mulder, Energy transition for the market or from within society?, Conference: "Energy communities for collective self-consumption", Université de Grenoble, 23 June 2020 (https://ecosesa.univ-grenoble-alpes.fr/eco-sesa-program/news/replay-energy-communities-conference-839536.htm)

Master thesis

Elena Georgarakis (July 2020). Title: "Energy exchange between households: What are the preferences of return for exchanging locally generated renewable energy in the Netherlands?". M.Sc. Thesis Sustainable Development Energy & Materials Track (GEO4-2321). Master programme Joint International Master in Sustainable Development. Supervisors: Dr. Tarek AlSkaif (UU) and Mrs. Anne-Marie Pronk (ECF).

Marc Cañigueral Maurici (April 2020). Title: “Impact of electric vehicles flexibility in existing prosumer community”. M.Eng. Practicum report in Smart Cities Master programme, Universitat de Girona, in collaboration with and supervised by Hugo Niesing and Avi Ganesan (Resourcefully).

Gijs van Leeuwen (Sep 2019). Title: "Modelling an integrated blockchain-based energy optimization platform with bilateral trading for microgrid communities". M.Sc. Thesis Energy Science (GEO4-2510). Supervisors: Dr. Tarek AlSkaif (UU) and Prof. Wilfried van Sark (UU).

Press

Balanceerkunst, Blockchain kan energienet in evenwicht houden, de Ingenieur, Augustus 2020, pp. 13-16. (met Tarek AlSkaif)

PR of project and further PR possibilities

The project partners would like to be approached for any further publicity activities and would like to contribute to public activities of the Rijksdienst voor Ondernemend Nederland or the TKI-Urban Energy and are happy to add these insights to the debate about the energy transition in the Netherlands.

References

[1] P. Palensky and D. Dietrich, "Demand side management: Demand response, intelligent energy systems, and smart loads," *IEEE transactions on industrial informatics,* vol. 7, no. 3, pp. 381-388, 2011.

[2] CBS, "Hernieuwbare elektriciteit; productie en vermogen," Centraal Bureau voor de Statistiek (CBS), 2017. [Online]. Available: http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=82610ned&D1=7&D2=5&D3=24-26&HDR=T&STB=G1,G2&VW=T. [Accessed 29 Nov 2017].

[3] NEA, "Statistics Electric Vehicles in the Netherlands," Netherlands Enterprise Agency, 2017. [Online]. Available: https://www.rvo.nl/onderwerpen/duurzaam-ondernemen/energie-en-milieu-innovaties/elektrisch-rijden/stand-van-zaken/cijfers. [Accessed 11 Dec 2017].

[4] RVO, "Plan van Aanpak elektrisch vervoer: 'Elektrisch Rijden in de Versnelling'," Rijksoverheid, [Online]. Available: https://www.rijksoverheid.nl/documenten/richtlijnen/2011/10/03/bijlage-2-plan-van-aanpak-elektrisch-vervoer-elektrisch-rijden-in-de-versnelling. [Accessed 11 Dec 2017].

[5] RVO, "Rijksoverheid stimuleert duurzame energie," Rijksoverheid, [Online]. Available: https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/meer-duurzame-energie-in-de-toekomst. [Accessed 11 Dec 2017].

[6] CBS, "Zonnestroom naar sector, 2015," Centraal Bureau voor de Statistiek, 2016. [Online]. Available: https://www.cbs.nl/nl-nl/maatwerk/2016/51/zonnestroom-naar-sector-2015. [Accessed 11 Dec 2017].

[7] L. Minchala-Avila, L. Garza-Castanon, A. Vargas-Martinez and Y. Zhang, "A review of optimal control techniques applied to the energy management and control of microgrids," *Procedia Computer Science,* vol. 52, pp. 780-787, 2015.

[8] S.-C. Tsai, Y.-H. Tseng and T.-H. Chang, "Communication-Efficient Distributed Demand Response: A Randomized ADMM Approach," *IEEE Transactions on Smart Grid,* vol. 8, no. 3, pp. 1085 - 1095, 2015.

[9] S. Mhanna, A. C. Chapman and G. Verbic, "A Fast Distributed Algorithm for Large-Scale Demand Response Aggregation," *IEEE Transactions on Smart Grid,* vol. 7, no. 4, pp. 2094-2107, 2016.

[10] PARENT, "Participatory platform for sustainable energy management (PARENT)," 1 Jul 2016. [Online]. Available: http://www.parent-project.eu/. [Accessed 1 Mar 2018].

[11] G. Litjens, E. Worrell and W. van Sark, "Influence of demand patterns on the optimal orientation of photovoltaic systems," *Solar Energy,* vol. 155, pp. 1002-1014, 2017.

[12] EURELECTRIC. Prosumers – an integral part of the power system and the market. Eurelectric 2015, http://www.eurelectric.org/ media/178736/prosumers_an-integral_part_of_the_power_system_and_market_june_ 2015-2015-2110-0004-01-e.pdf

[13] Ma Z, Xie J, Li H, Sun Q, Si Z, Zhang J, Guo J. The role of data analysis in the development of intelligent energy networks. IEEE Network 2017;31(5):88–95. https://doi.org/10.1109/MNET.2017.1600319.

[14] AlSkaif T, Luna AC, Zapata MG, Guerrero JM, Bellalta B. Reputation-based joint scheduling of households appliances and storage in a microgrid with a shared battery. Energy Build 2017;138:228–39. https://doi.org/10.1016/j.enbuild.2016. 12.050.

[15] Andoni M, Robu V, Flynn D, Abram S, Geach D, Jenkins D, McCallum P, Peacock A. Blockchain technology in the energy sector: a systematic review of challenges and opportunities. Renew Sustain Energy Rev 2019. https://doi.org/10.1016/j.rser. 2018.10.014.

[16] Yli-Huumo J, Deokyoon K, Choi S, Park S, Smolander K. Where is current research on blockchain technology? – a systematic review. PLoS ONE 10 (11). doi:https:// doi.org/10.1371/journal.pone.0163477.

]17] K. Christidis and M. Devetsikiotis, "Blockchains and Smart Contracts for the Internet of Things," *IEEE Access,* vol. 4, pp. 2292 - 2303, 2016.

[18] PricewaterhouseCoopers, "Blockchain – an opportunity for energy producers and consumers?," PWC global power & utilities, 2016.

[19] M. Swan, Blockchain: Blueprint for a new economy, O'Reilly Media, Inc, 2015.

[20] Nakamoto S. Bitcoin; 2019. https://bitcoin.org/bitcoin.pdf.

[21] Wood G. Ethereum: a secure decentralised generalised transaction ledger, Ethereum Project Yellow Paper. https://ethereum.github.io/yellowpaper/paper.pdf.

[22] L. Hagström and O. Dahlquist, "Scaling blockchain for the energy sector," Uppsala Universitet, 2017.
[23] Dong, Z.; Luo, F.; Liang, G. Blockchain: a secure, decentralized, trusted cyber infrastructure solution for future energy systems. J. Mod. Power Syst. Clean Energy 2018, 6, 958–967, doi:10.1007/s40565-018-0418-0.
[24] Mengelkamp E, Gärttner J, Rock K, Kessler S, Orsini L, Weinhardt C. Designing microgrid energy markets: a case study: the Brooklyn microgrid. Appl Energy 2018;210:870–80. https://doi.org/10.1016/j.apenergy.2017.06.054.
[25] U. Papajak, "Can the Brooklyn Microgrid project revolutionise the energy market?," 2017. [Online]. Available: https://medium.com/thebeammagazine/can-the-brooklyn-microgrid-project-revolutionise-the-energy-market-ae2c13ec0341. [Accessed April 2018].
[26] Münsing E, Mather J, Moura S. Blockchains for decentralized optimization of energy resources in microgrid networks. In: 2017 IEEE conference on Control Technology and Applications (CCTA), IEEE; 2017. p. 2164–71.
[27] P. Ltd, "PowerLedger," Power Ledger Ltd, 2017. [Online]. Available: https://powerledger.io/. [Accessed April 2018].
[28] WePower, WePower , 2017. [Online]. Available: https://wepower.network/. [Accessed April 2018].
[29] M. Mihaylov, S. Jurado, N. Avellana, K. Van Moffaert, I. Magrans de Abril and A. Nowé, "NRGcoin: Virtual Currency for Trading of Renewable Energy in Smart Grids," in *European Energy Market (EEM), 2014 11th International Conference on the*, Krakow, 2014.
[30] Buth, M.; Wieczorek, A.; Verbong, G. The promise of peer-to-peer trading? The potential impact of blockchain on the actor configuration in the Dutch electricity system. Energy Res. Soc. Sci. 2019, 53, 194–205, doi:10.1016/j.erss.2019.02.021.
[31] Van Leeuwen, G.; AlSkaif, T.; Gibescu, M.; Van Sark, W. An integrated blockchain-based energy management platform with bilateral trading for microgrid communities. Appl. Energy 2020, 263, 114613, doi:10.1016/j.apenergy.2020.114613.
[32] AlSkaif, T.; Van Leeuwen, G. Decentralized Optimal Power Flow in Distribution Networks Using Blockchain; Institute of Electrical and Electronics Engineers (IEEE): New York, NY, USA, 2019; pp. 1–6, doi:10.1109/sest.2019.8849153.
[33] Diestelmeier, L. 'Changing Power: Shifting the role of electricity consumers with blockchain technology - Policy implications for EU electricity law', Energy Policy 128 (2019).
[34] Lavrijsen, S. 'Power to the energy consumers' in Eur. Energy. Environ. Law Rev. 172-186 (2017)
[35] Oliver, J and Sovacool, B. 'The energy trilemma and the smart grid' in Asia Pac. Policy Stud. 4 (1), 70-84
[36] DiLund, P. et al 'Review of energy system flexibility measures to enable high levels of variable renewable electricity' Ren. En. Sustain. En. Review 45, 785-807.
[37] Renewable Energy Directive, Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources.
[38] Energy Market Directive, Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU.
[39] Besluit experimenten decentrale duurzame elektriciteitsopwekking. 28/02/2015
[40] Schneiders, A. and Shipworth, D. 'Energy cooperatives: a missing piece of the peer-to-peer energy regulation puzzle?' UCL Energy Institute, August 2018
[41] Taylor JA. Convex optimization of power systems. Cambridge University Press 2015. https://doi.org/10.1017/CBO9781139924672. https://www.cambridge. org/core/product/identifier/9781139924672/type/book.
[42] Wang S, Taha A, Wang J, Kvaternik K, Hahn A. Energy crowdsourcing and peer-to-peer energy trading in blockchain-enabled smart grids. IEEE Trans Syst Man Cybernet: Syst. 49 (2019) 1612-1623.
[43] Baroche T, Moret F, Pinson P. Prosumer markets: a unified formulation. In: IEEE PowerTech conference; 2019, Milano, Italy. p. 1–6.
[44] Low SH. Convex relaxation of optimal power flow-part i: formulations and equivalence. IEEE Trans Control Network Syst 2014;1(1):15–27.
[45] Boyd S. Distributed optimization and statistical learning via the alternating direction method of multipliers. Found Trends Mach Learn 2011;3(1):1–22. https://doi.org/10.1561/2200000016.
[46] Solidity language documentation, https://solidity.readthedocs.io/en/v0.7.3/

[47] Ethereum, Web3.py; 2019. https://github.com/ethereum/web3.py.
[48] Diamond S, Boyd S. Cvxpy: A python-embedded modeling language for convex optimization. J Mach Learn Res 2016;17(1):2909–13.
[49] TruffleSuite, Ganache-cli; 2019. https://github.com/trufflesuite/ganache-cli.
[50] EHPC, East Harbour Prosumers Community platform for sustainable energy use; 2019. http://www.prosumers.nl/ .
[51] N. Li, L. Chen, S. H. Low, Exact convex relaxation of OPF for radial networks using branch flow model," in 2012 IEEE Third International Conference on Smart Grid Communications (SmartGridComm). IEEE, 2012, pp. 7–12.
[52] European Power Exchange Netherlands (EPEX), Day-ahead auction; 2019. http://www.apxgroup.com/trading-clearing/day-ahead-auction/.
[53] Gerritsma MK, AlSkaif TA, Fidder HA, van Sark WG. Flexibility of electric vehicle demand: analysis of measured charging data and simulation for the future. World Electric Veh J 2019;10(1):14.
[54] Kim B, Baldick R. A comparison of distributed optimal power flow algorithms. IEEE Trans. Power Syst. 2000;15(2):599–604. https://doi.org/10.1109/59.867147.