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DESIGN OF AN OPEN-SOURCE LABORATORY DEMONSTRATOR FOR PEER-TO-PEER TRADING IN LOCAL ENERGY MARKETS

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Abstract

There is significant research interest in new energy trading mechanisms based on peer-to-peer or community-based markets, which are more consumer-centric and direct compared to traditional electricity retail markets. Such trading mechanisms require an electricity trading platform that can manage and settle energy transactions from vast numbers of small distributed energy resources, and therefore scalability and interoperability are major challenges. The hardware, communications and software required for implementing local energy trading platforms needs to be designed, tested and demonstrated in a real-time environment. Accordingly, this paper presents a design for an open-source laboratory demonstrator, which allows testing of the hardware and software required for peer-to-peer local energy trading using distributed ledger technology.

1 Introduction

Electrical energy systems are currently experiencing fundamental changes, driven by two major technology trends: 1) the adoption of distributed energy resources such as renewable generation and the electrification of transport and heating; and 2) the extension of communications and control technology to the individual user level [1–3]. At the same time, there is a social and political movement towards environmentally-sustainable energy systems. Many power systems worldwide have already divested from conventional, centralised generating plant and are now dealing with the large-scale integration of highly-dispersed renewable generation [4]. However, it is widely recognised that existing power grids are not flexible or decentralised enough to cope with the transition to a future system based almost entirely on distributed renewable energy sources [5–7].

There is a need for the development of appropriate markets and control architectures to support a more decentralised and consumer-centric power system. Despite much interest in the development of microgeneration and microgrids [8], it has remained difficult for those with small-scale, distributed energy resources to fully participate in wholesale energy markets, due to barriers to market entry, such as minimum size requirements and a lack of appropriate economic incentives [9, 10].

The last several years have seen a significant research drive in the area of local electricity markets, designed to enable small users with local resources to trade and exchange energy with each other directly on a “peer-to-peer" basis, or within local communities [11, 12]. Many have envisaged a future where electricity grids are fully digitalised, with grid assets and services “tokenised" using Distributed Ledger Technology (DLT) [13] as an automated means of recording, settling, and securing energy micro-transactions in future decentralised electricity markets [14].

2 Literature Review

Some works from 20-25 years ago [15, 16] explored the concept of coordinated multilateral trades for electric power networks, mainly as a point of academic discussion around centralised versus decentralised power market structures [14]. Recently, peer-to-peer (P2P) electricity trading has emerged as a potential solution for developing more decentralised and consumer-centric electricity market structures [17]. In its simplest form, a P2P market is a collection of multi-bilateral trading agreements between agents. P2P concepts originated in computer science as a means of sharing and distributing data between multiple computers [18, 19].

Applying such concepts in power systems would require the co-ordination of a range of Distributed Energy Resources (DER) at multiple levels and scales throughout the power system. Several recent works (e.g. [17, 20]) have attempted to develop P2P electricity market designs. Such decentralised market architectures can be in the form of a “full P2P" design, where each peer in the network is capable of directly trading with any other peer, or may have a more structured “community-based" design, where each local area has a community manager that manages transactions within the local community, and interactions with the rest of the electricity system.

Recent work has proposed market designs for energy trading between small-scale electricity producers and consumers in low voltage distribution networks [21, 22] and in microgrids [23, 24]. The transactive energy approach outlined in [25, 26] aims to provide a network environment for distributed energy nodes, with “horizontal" transactions (e.g. P2P transactions) in place of, or in addition to, traditional “vertical" transactions (e.g. price signals sent to the end user from an upstream network operator).

Methods for carrying out P2P energy trades between buyer and seller agents using an double auction mechanism were proposed in [27] and [28]. Consortium-based approaches to energy trading and scheduling strategy in P2P systems have also been investigated [29, 30]. Transactive energy trading methods for local energy trading based on the Alternating Direction Method of Multipliers (ADMM) are proposed in [31, 32]. In industry, a number of P2P energy trading trials and demonstration projects have been carried out to date (e.g. [33–37]). Scalability and interoperability are significant challenges in this field, and at the time of writing, there are active working groups engaged in the early development of IEEE standards for transactive energy systems [38] and DLT applications in energy [39].

However, a significant gap in the existing literature is that the hardware and software required for implementing local energy trading platforms needs to be specified in detail and demonstrated in a realistic power network environment. This paper addresses this gap by presenting an open-source laboratory demonstrator which allows testing of the hardware and software required in order to implement P2P energy trading. This demonstrator provides an interface between home/building smart meters and a local energy trading platform, based on automated smart contracts that are secured using DLT.

3 Methodology

3.1 Design Objectives

The main objective of this work is to provide an open-source laboratory demonstrator in order to carry out end-to-end testing of the hardware, communications and software required for P2P electricity trading in local energy markets. The design objectives for the demonstrator were as follows:

- Design a functional interface between building electricity smart meters and blockchain/DLT software.
- Create use cases which demonstrate the triggering of an automated smart contract for energy trading based on measurements from home/building smart meters.
- Develop a demonstrator system based entirely on open-source hardware and software.

It should be noted that this work deals only with the hardware and software architecture required in order to execute peer-to-peer trades in a local energy market. The process of designing such a local energy market (e.g. identifying and matching of buyer/seller peers and bids/offers, market clearing and settlement), is outside of the scope of this paper. Instead, the aim of this paper is to develop an open-source test environment that can be used to test various approaches to local energy market design and implementation. Similarly, issues related to the system integration of local energy markets, such as the allocation of network charges and losses, are also beyond the scope of this work.

3.2 Open-source Smart Metering

The original intention of this work was to interface the blockchain/DLT software with utility-grade smart metering systems, of the same type and specification used in residential and small commercial buildings. However, there were some practical problems with the use of utility smart meters: 1) the full details and specification of the smart metering device to be used in the national smart meter rollout in Ireland were not available at the beginning of this research project; 2) procurement of these devices was difficult as they are generally not sold to individuals; and 3) there were issues with accessing the firmware and data streams from utility-grade meters.

Therefore an open-source solution was preferable, and dedicated open-source “EmonPi" devices from Open Energy Monitor [40] were used. These were interfaced with the Open Energy Monitor data management platform “emoncms” [41], which provides an open-source service for processing, logging and visualising energy data. Figure 1 shows the EmonPi open-source monitoring device with clamp meter and WiFi antenna, and a typical installation of the device at a household mains supply.

Fig. 1 EmonPi open-source monitoring device with clamp meter and WiFi antenna, and EmonPi installation at household mains supply.

3.3 Middleware API

A middleware API was developed to interface the smart meter energy monitoring feeds with the DLT software via an Application Programming Interface (API). A RESTful web service was created using NodeJS backend. This provides a software interface to communicate with the smart meters, and stores trade information in a MongoDB database. The API also provides hour-ahead energy capacity forecasting for each prosumer using a simple exponential moving average forecast, and supplies readings to the frontend. Three separate APIs are supported by the middleware:

1. */trade* which accepts POST requests for a specific kWh amount of energy.
2. */readings* which queries the meters and returns readings for the specified duration.
3. */tradeList* which accepts GET requests and returns all the trades that have been placed.

First, a consumer and a producer for P2P energy trading are identified, and the consumer sends a request for a specific kWh amount of energy. The API checks if the required energy capacity is available from the producer and if so, sends a response, indicating that capacity is available and starts the trade. Figure2 shows the REST API diagram for the system, indicating how requests travel from the DLT software through the middleware component.

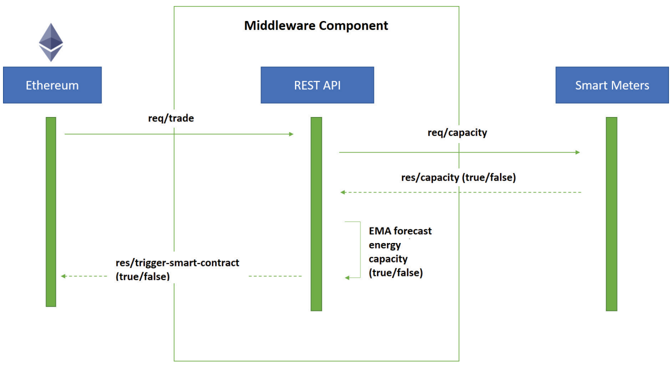

Fig. 2. REST API diagram for the system.

3.4 *Ethereum-based Execution of Smart Contracts*

Ethereum Studio [42] is used for demonstrating the execution of automated smart contracts for energy trade payments. Once the consumer and producer peer for a particular transaction have been identified, the peers form a smart contract between them. For example, if peer m_i decides to sell x units of energy at price y between time $[t_1, t_2]$, and peer m_j is to buy x units of energy at price y between time $[t_1, t_2]$ then, the smart contract will involve two parties m_i and m_j, it will be funded by m_j with energy tokens of value $x * y$.

This smart contract can be automatically triggered based on measurements from the energy monitoring installed at peers m_i and m_j and the energy measurements determine the actual payment. For example, say m_i contributes $x_1 < x$ units of energy. Hence it will be paid $x_1 * y$ tokens and $(x - x_1) * y$ tokens will be sent back to m_j. The energy tokens are part of the DLT infrastructure for energy trading and peers can purchase these tokens with other currencies (e.g. euros or dollars). For full details of the approach used for energy tokenisation, the reader is referred to [28] and [43].

4 Proposed Demonstrator Design and Testing

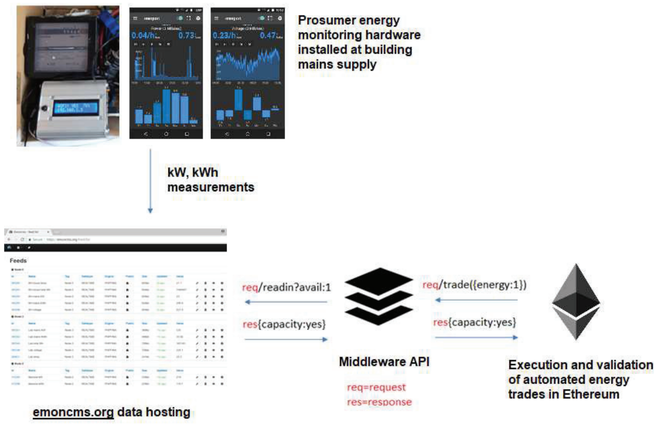

Fig. 3 Overview of the proposed design for the peer-to-peer energy trading laboratory demonstrator.

Figure 3 shows an overview of the proposed design for the P2P energy trading laboratory demonstrator. Three EmonPi prosumer energy monitoring devices are set up to monitor and log quantities including kW power, cumulative kWh energy, voltage, and temperature at 10 second intervals. These data are available from two residential homes, which provide the “consumer" demand profiles, and from a university power engineering laboratory, which provides a generation emulator in order to serve as a “producer" for P2P energy trading. The proposed approach for testing the system for P2P energy trading end to end is as follows:

- Consumer
  1. A load is switched on in one of the monitored residential homes, e.g. water heater.
  2. The amount of energy consumed by the load is metered using the Emonpi.
  3. Metered consumption is pushed onto the Ethereum blockchain via the middleware API.
- Producer
  1. Generation capacity is forecasted and validated using the EmonPi.
  2. If capacity is available, an automated smart contract is triggered.
  3. Exported generation is metered and validated using the EmonPi.

Figure 4 shows a sample of the smart metering measurements, showing two metered houses (the "Consumers"), and the emulated generation in the university power electronics laboratory ("Producer") . The values for the Lab Generator were obtained by reversing the direction of a measurement of one of the three supply phases to the lab. This generator could also be implemented using for example, a solar PV panel output, or any other generation or generation emulator device.

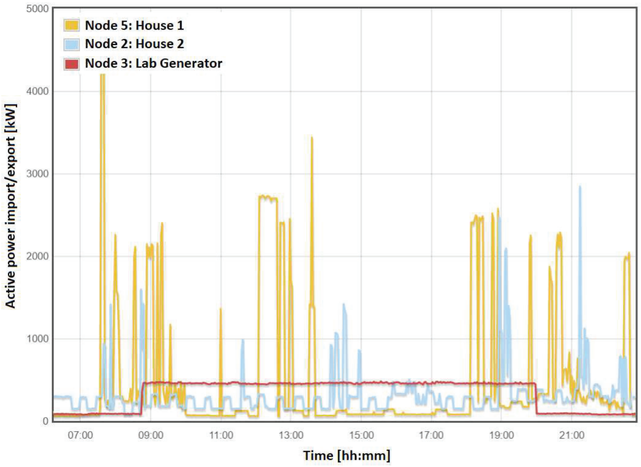

Fig. 4 Sample of smart meter measurement data showing active power measurements from House 1 and 2 ("Consumers") and lab emulated generation ("Producer").

The process for settlement of automated P2P electricity trades was carried out at five-minute intervals, and several preliminary tests were carried out in order to demonstrate that the interface between the EmonPi smart metering hardware and the DLT software operates correctly. This testing provides a simple proof-of-concept by demonstrating that Ethereum-based smart contracts can be automatically triggered and executed based on real-time measurement data from local consumer and producer smart meters.

It should be noted that these experiments used a Truffle-based [44] implementation of Ethereum. The network had six nodes. On average the time it took from the trade requests (from smart meters) to transaction creation is between six to ten seconds. However, due to the small size of network used in this experiment such transaction completion times may not be relevant. Larger networks may need more time to confirm a transaction. The relationship relation between transaction completion time and the size of the network was investigated in [12].

In this paper, a method was devised to estimate the average transaction completion time and properties of the blockchain peer to peer network including the number of nodes, number of transactions created per second, communication delay, and computation power of the nodes. The workflow used to determine an appropriate blockchain using is shown in Figure 5. First, the properties of a blockchain network to be built in terms of size of the network and network delay are fixed. These parameters are used as input to the blockchain simulator. Next, the expected number of forks and expected throughput of the network are determined using the results from the execution of the simulation.

This estimation was used to predict the blockchain network suitable for type of peer to peer energy trade (energy trade time constraint). In other recent work by the authors [45],

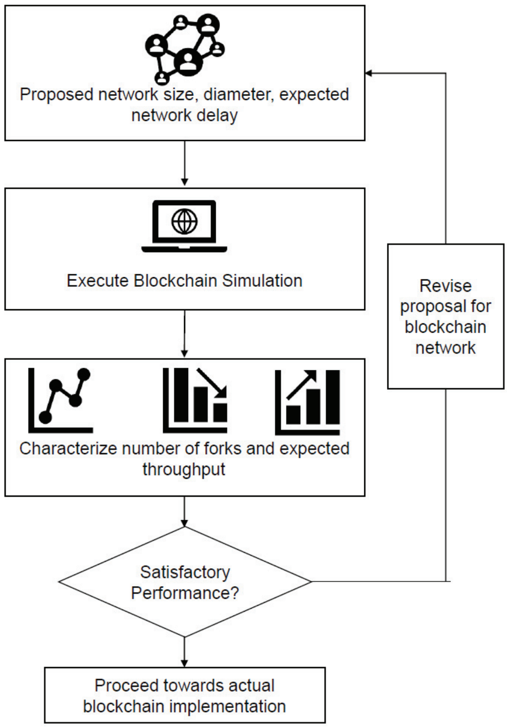

Fig. 5 Workflow used in order to determine the blockchain to be implemented.

blockchain offline channels are used for payments between the peers. In such a trading system, the time for payment from one peer to another peer (with a mutual channel) is the communication time required to to send three messages (each peer). This is expected to require less than six seconds. The real-time transaction confirmation with a high transaction throughput (scalability) is a massive challenge for designing blockchain for peer to peer energy trading. The authos aim to design such a blockchain in the CENTS project [46].

5 Conclusions and Future Work

This paper reports on ongoing research in the development a laboratory demonstrator for P2P electricity trading in local energy market based on open-source hardware and software, and presents preliminary results from the EnerPort [47] and CENTS research projects [46]. This work has demonstrated a functional interface between the metering hardware and the DLT software, and has provided a simple demonstration of automatic triggering and execution of P2P electricity trades using smart contracts.

A significant amount of further work is required in testing of the prosumer monitoring equipment and communications, and real-time validation of hardware and software performance and reliability. Further development of the market mechanisms used to trade energy within local communities is also required. In particular, a forward market for local energy trading needs to be developed, along with a method for settlement of imbalances, in order to deal with situations where a consumer or producer's actual energy import/exports do not match with their forward market commitments.

Future work in the CENTS project [46] will build a specific home energy management hardware device for prosumer monitoring and on-site energy resource management. This device will act as an interface with local electricity trading platforms, and as an automated agent that carries out trades based on the home user's preferences. The CENTS local energy trading platform and its hardware and software will be demonstrated in full-scale user trials by the end of the project.

Scalability is an important aspect of this, since, in a future decentralised, prosumer-based electricity market, it will be necessary to have a system that can manage and settle transactions from very large numbers of small DER. Such a transaction management system should have an open architecture, in order to easily register new market entrants and accommodate emerging DER technologies. Further work will also define specifications for harmonised data exchange between individual prosumers, community energy managers, and DSO/TSOs in order to facilitate the large-scale implementation of open energy trading platforms, and a detailed framework for data exchange, outlining data formats, structures, classifications, and applications will be developed.

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