User-Centred Energy Systems

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P2P, CSC and TE: A Survey on Hardware, Software and Data

Systematic Review

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1. Introduction

Global population is expected to grow significantly over the next 30 years, expecting to hit almost 11 billion by 2050 [1], coupled with the electrification of heating, cooling and transport, this will have a profound effect on electricity consumption and demand [2]. The development of potential solutions to address this problem is of great importance. Peer-to-peer (P2P), Community Self-Consumption (CSC) and Transactive Energy (TE) energy business and sharing models offer an innovative and exciting opportunity, but extensive obstacles and challenges as well.

Discussions around implementation of such opportunities is vital if we are to tackle the Sustainable Development Goals [3] in relation to energy poverty, as energy is seen to be vital for improving living conditions and household capability [4].

However, the underlying challenges to the widespread adoption of these models are numerous [5]. As new renewable (and distributed) energy resources become available, the grid matrix becomes more complex to manage and integrate. The standardisation efforts, or the inadequacies they possess, poses serious difficulties as it can have high granularity with a diverse range of hardware and software implementations. Additionally, energy storage in distributed generation is very important as it needs to be flexible enough to support decentralised energy schemes, as it must be the basis to tackle unbalanced supply and demand scenarios.

To accomplish that, decentralised energy schemes, such as P2P rely on a whole set of dedicated hardware and software solutions. Therefore, such granular implementation and its integration to the power grid will demand state-of-the-art management systems [6]. Very innovative solutions [7] to support data integration, enhanced management features and trading functionalities [8] should be in place - and understanding this environment is imperative.

However, the researchers and practitioners are challenged with the task of remaining well informed of the relevant developments on the topics of decentralised energy generation and use, given the:

- current rapid developments in the research and practice on this topic, driven by the world-wide energy decarbonisation agenda, and
- the wide set of relevant disciplines and knowledge areas - ranging from the power systems aspects of hardware, to networking and telecommunications; from software platforms for energy transacting to regulations on data protection and privacy.

This paper provides a concise overview of the current state of practice on hardware, software and data research topics for the P2P, Community Self-Consumption (CSC) and Transactive Energy (TE) energy business and sharing models. To the novice entrants into this vibrant field of research and development, this paper aims to serve as a guide that signposts the key directions of the ongoing work and to outline the breadth and the depth of the relevant issues. To those already working in this domain, the paper aims to provide a consolidated update on the current state of the wider field.

To provide this concise overview, the paper presents a structured literature review on the topics of hardware, software and data for the three previously noted decentralised energy models.

The paper is organised as follows:

Section 2 describes briefly the methodology used to choose all the material supporting this research. Section 3 brings a comprehensive compilation of the main hardware devices used on P2P, Community Self-Consumption (CSC) and Transactive Energy (TE) implementations. Section 4 then describes a comprehensive compilation of software (including blockchain) commonly used in P2P, Community Self-Consumption (CSC) and Transactive Energy (TE) . Similarly, Section 5 addresses some software features but with focus on interfaces and applications. Section 6 explores the data aspect of P2P, especially in the aspect of its diversity and integration issues. Section 7 explores the P2P, Community Self-Consumption (CSC) and Transactive Energy (TE) main concepts, with reference to its advantages and disadvantages. Section 8 studies a selected varierty of P2P, Community Self-Consumption (CSC) and Transactive Energy (TE) projects and, finally, Section 9 discusses the main topics brought by this research. Additional supporting materials (acronyms and abbreviations, and an appendix with an extensive list of projects that were reviewed during this research) are attached.

2. Methodology

This paper employed a structured approach to the literature review, aiming to answer the following questions:

1. What hardware and software were mentioned by P2P, CSC and TE projects (and were they trialled)?
2. What data was gathered, what was it used for and who had access to it?
3. What areas existed in the available documentation (publications, reports, white papers and websites) that require further research?

Initially, the research focused on gathering publications, reports and associated information related to P2P, CSC and TE projects and trials using relevant keywords.

Then the structure was divided up into the following four categories, hardware, software, data and projects. Each paper gathered was then evaluated looking for the above terms and associated words (such as "Inverter", "Network", "Tool", "Pilot", "Demo", "Trial") with a matrix developed to determine if the source contained these words. This matrix helped inform the reviewers if the projects warranted further investigation (for example, projects with numerous mentions in publications, ticking the relevant categories, project websites, reports, publications). In short, the goal was to help find projects that could answer the above questions and had a correspondent that could be contacted in further stages of the work of the Global Observatory on Peer-to-Peer, Community Self-Consumption and Transactive Energy Models (GO-P2P), to elicit more details that may have been lacking in publications or other such documentation.

3. Hardware

3.1 Hardware requirements

Transactive energy systems, including that of a P2P energy trading system, require end-use devices utilised with the smart grid environment. These control devices may be categorized as [9,10].

- Passive
- Active
- Interactive
- Transactive Controllers
- Communications
- Controllers and Actuators

Passive
In short, a passive device is an uncontrolled element with no input regardless of its system's frequency, congestion, peak prices and so on.

Active
Active devices are intelligent devices that respond autonomously to the reduction of consumption in accordance with the principle of demand response. The autonomous response does not enable users to have a direct input interface that would allow control of items such as consumption reduction processes.

Interactive
Interactive devices allow for limited interaction. Consumers can interact to adjust the consumption of electricity, but still cannot regulate it as per peak prices for example.

Transactive Controllers
These controllers are envisaged to be the most advanced form of devices which can exchange information between consumers, grid, aggregators and so on.

This information can be about electricity prices, line congestion, frequency, resulting in the system as a whole to determine a more efficient way to operate and provide a win-win situation, to every consumer participating in it.

These particular devices are the most favourable with regards to community P2P energy trading markets, as they possess characteristics that are optimal for a P2P framework, and allow both prosumers and active consumers to make trades in real time. The transactive control device is primarily an energy gateway which exchanges information for energy transactions [11]. Transactive Energy markets (P2P and local energy market) require such controllers to communicate with the various hardware types such as smart meters, sensors, prosumer energy metering and EMS hardware.

In context, the cooperative P2P energy trading market with two hardware devices; Smart Meters and Home Energy Management System (HEMS), at the prosumer or active consumer premises, is vital in disrupting the energy market.

Smart meters are the intelligent metering infrastructure which is believed to be replacing the traditional meters, offer transition to a low-carbon energy system, by enabling better energy awareness amongst the participating consumers. It may also present sufficient information such as providing users access to accurate information on energy usage throughout the day, variable electricity pricing and also exhibit demand response capacities obligatory for a prosumer to participate in bidding/auction processes. Smart meters then could be defined as an enabling piece of hardware which will incentivise the prosumers through P2P and other markets. Thus, it is important to mention that the smart meters should be capable to engage in the task of participating in the blockchain platform by having sufficient computational power to track and trace the number and complexity of smart contract transactions. On the other hand, the Home Energy Management System (HEMS), is a hardware environment installed in the consumers' home and acts as behind-the-meter technology envisaged to converge three large consumer segments- smart heating, home entertainment and home security systems. These can be used to control the on-site devices and aid the consumer in contributing to demand response.

3.2 Communications

Controllers and Actuators

To support the Home Energy Management System (HEMS) in controlling a variety of household devices, actuators are needed.

Controllers can control and monitor electrical appliances while actuators constitute a final element to take actual physical action. The controller with certain optimization algorithms determines when to command actuators to turn on or off power to the particular appliances. This command is known as an information trigger. In the context of demand response, the pre-designated trigger is responsible for actuating the response received by an actuator. Notification, pricing and control signals, local demand and frequency are a few triggers also included [12]. Based on types of technique used for scheduling loads, the Home Energy Management System (HEMS), controllers can be categorized into three categories [13]:

- Rule-based Controller.

- Artificial Intelligence-based Controller.
- Optimization Methodology-based Controller.

Rule-based controllers are the most straightforward way to realize a control operation in home automation. The control action is carried out based on some condition being met or violated possibly by developing some if/then ruling set. These ruling sets may include load shifting based on low-prices, load priority, a decrease in energy cost, etc. Being a most simple control approach, it possesses certain shortcomings that cannot be extended for Demand Response and inevitably Blockchain applications due to the very limited data handling capabilities [14,15].

Recently, AI based controllers found their application in the Home Energy Management System (HEMS) controller, as it can overcome the limitations of the Rule-based controllers. A controller that mimics a human decision making and thinking process would be ideal for scheduling control in smart homes. These controllers provide quick response on fast solution based predictions [16-18].

The only drawbacks of such controllers is long learning and training times, which affects the solution and controller speeds. Moreover, there is no provision of addressing user preferences. To counter the shortcomings of the AI based controllers, optimization based controllers seems to be a perfect fit for scheduling intelligent control. These controllers are based on optimization methods capable of providing a suitable solution based on user preferences.

These user preferences are realized as constraints subjected to determining (minimizing or maximizing error, cost, design, energy management) an objective function. A few applications include minimization of the electricity cost, optimal consumption schedule, minimizing tariffs for end users, controller scheduling with storage, optimal day-ahead scheduling, and so on [19-23].

Control Relays/actuators are the final elements to realize load control. These actuators work as load controllers, switching connected appliances on and off to minimise base-load energy consumption. This is done via smart plugs, and power to the plug socket is cut when the system senses that the power consumption of the connected appliance corresponds to standby mode, or when external environmental conditions are met.

The Home Energy Management System (HEMS), may include a number of sensors depending on the diversity and number of appliances that should be controlled. These sensors are connected through wireless communication to a common actuator. This network of sensors along with actuators, known as Wireless Sensor and Actuator Network (WSAN), provides capability for different nodes to communicate with each other and carry out an actuation action. The plugged in electrical loads like a television, fan, washing machine, vacuum cleaner, lighting, etc. may be switched on or off by receiving a command from the actuator. Actuators send control commands to modify the switching status of a particular load through power socket sensor. For this the actuators usually require consumption data and status of the loads.

If there are large number of sensors in a house, separate sensor sets will be controlled by varying other actuators [24-26]. The actuators may be a flush mounted device, plugs or in-built device- for example, a switching actuator, dimming actuator, multi-heating actuator, and thermostat actuator [27]. It should be noted that these actuators are low level computational hardware that cannot make information processing to and from a blockchain due to their limited computational capacities. Further research is required so that even these hardware may communicate with the blockchain platform with some additional low cost computational element embedded in the hardware.

3.3 Hardware Data (Smart Meters, Actuators, Sensors, etc.)

Typically, mechanical meters collect data on an hourly or monthly basis, whereas more modern smart meters collect data by the minute.

Grid operators have access to large volumes of data, from the massive number of devices connected to the power grid such as generators, breakers, or even information about individual appliances in commercial or residential buildings. This massive amount of data comes from multiple sensor networks across transmission and distribution systems [28]. Data is gathered from various sources, such as electricity costs, billing information, Phasor Measure Units (PMU), smart meter measurements, weather conditions and SCADA. It is necessary that the data is made available so that useful information can be obtained [28].

3.4 Monthly energy collection by smart meters

Energy meters gather monthly information about household electricity consumption. As the meter may not read the energy usage at a set time interval, the data provided by the meter may be limited.

A smart meter provides information on voltage (V), real power (watt), and apparent power (VA) consumption at a 15-minute sampling rate. It is possible to collect monthly data and report it from a given start and end date [28]. It is recommended that, if billing is the sole purpose, reporting monthly data will reduce communication needs between the meter and control centre [28].

3.5 Daily energy collection by smart meters

Energy consumption may reveal minimum, average and maximum energy consumption on a daily basis in a household [28]. This information can be used to derive occupancy, number of individuals in a household and activity in the household. Since this information is strictly private, consumers may raise concerns (i.e. General Data Protection Regulation (GDPR)). Daily consumption information varies due to weather conditions, individuals' behaviour and preference, occupancy, and therefore is of little use unless there is abnormality in energy consumption. However, in Home Energy Management System (HEMS), daily energy consumption information can be vital to monitor and trigger customer actions in case of abnormality [28].

3.6 Smart Sensors in a Smart Grid

Smart sensors are capable of recording very valuable information. These are intelligent devices deployed in the smart grid, some of which include temperature, pressure, humidity, voltage and current sensors. [29] describes the sensing functions, applications and network communication of PMU and Merging Unit (MU)-based Smart Sensors.

A PMU provides real-time synchrophasor data for advanced applications [29]. It is a device that produces synchronized phasor, frequency and ROCOF estimates using the input voltage and/or current signals [29].

- Current and voltage sensors provide analogue inputs for PMU, used to measure current waveforms and 50/60 Hz alternating current (AC) voltage, typically sampled at a rate of 48 samples per cycle [29].
- An internal clock records the timestamp for each sample and accurately synchronizes the time using a phase-locked oscillator [29].
- A processing module follows various steps. Signal conditioning is performed, followed by conversion of signals into digital form with timestamps using a phase-locked oscillator and alignment of phase data using GPS time reference of an external network time reference. Finally, the voltage and current phasors are computed, and synchronized phasor, frequency and ROCOF estimates are produced [29].
- The network communication module is used to communicate data with advanced applications.

A Merging Unit (MU)-based smart sensor provides real-time status of the power grid [29]. It is a device that samples Alternating Current (AC) signals in one or more phases. It converts the voltage and current signals into digital values, uses time synchronization to align multiple phases together and transmits the sampled values to protection replays [29]. The main functions of Merging Unit (MU)-based smart sensors include sensing, signal conditioning, conversion of analogue signals to digital values, data processing and merging, and network communication.

- Analogue current and voltage of the power grid are provided as inputs to Merging Units (MU).

- The internal clocks record the timestamps for each sample and accurately synchronize time with an external Coordinate Universal Time (UTC) source as a time reference [29].
- In the processing module, amplification and signal conditioning are performed, the analogue signals are converted into digital form based on data from a GPS receiver or external network time reference. An alignment algorithm is used to produce three time synchronized phases of voltages and currents [29].
- The network communication is used to communicate with intelligent electronic devices and applications, and the authors of [29] discuss IEEE Standards for PMU- and Merging Unit (MU)-based smart sensors that describe the standard that these devices follow, such as Insitute for Electrical and Electronic Engineers (IEEE) C37.118 Standard for PMU-Based Smart Sensors and IEEE 1815 Standard for Smart Sensors.

4. Software, including blockchain

Data is a major factor to be considered, General Data Protection Regulation (GDPR) 2016/679 in the European Union (EU) have put in place strict rules for the processing of data.

4.1 Blockchain

Blockchain is a transparent, reliable and network friendly approach that fulfills the requirements of security, privacy and payment transactions in distributed energy trading systems [30]. Blockchain is an emerging technology allowing public contracts and secure transactions over a peer-to-peer distributed network while ensuring security and privacy of user information [30] This secure system prevents information forgery as the data in the chain cannot be altered, while newly entered data must be verified [31].

The blockchain technology enables the storage, exchange and verification of data in a distributed manner, as well as traceability of activities and anonymity of users. Users are identified by cryptographic public keys which enables a high level of anonymity [30]. However, this is pseudonymisation and not anonymisation. This means that a user’s activities such as energy consumption patterns, timestamps, location etc. can be used to identify more sensitive information, [32] and [33] discuss the zero knowledge proof techniques used to address this anonymity based weakness.

Blockchain can be perceived as a trustless trust, that allows the facilitation of transactions and shared history between its users, and that it's trustworthy without the use of trust between users [34]. Thus it has high potential for allowing integrations into the network, such as smart meters, efficiently balancing the grid by harmonising the supply and demand in real-time [31]. Additionally, it facilitates electronic contracts, called smart contracts, between distributed energy traders and consumers. These smart contacts enable two or more users to participate in a trade contract with each other anonymously. It is essentially a transaction protocol that executes the terms of the contract [35]. In blockchain, smart contracts are stored with a unique address and are triggered by addressing a transaction to it. Then, according to the data included in the transaction that triggered the execution, it is automatically and independently executed on every node in the network in the given manner [35]. The data associated with a smart contract includes program logic, a unique contract identifier, owner of the contract, account balance and private data storage [30].

4.2 How is it beneficial to energy trading?

Blockchain can support energy trading of Plug-In Electric Vehicles (PEV), which dynamically enter and leave the smart grid network at different locations [30]. These features make blockchain an essential technology for contributing to the distributed energy trading market.

4.3 Comments on blockchain

As with many technologies, blockchain is not perfect. An increased use of a blockchain ledger will ultimately slow down its algorithmic speed, and increase its dependencies on resources. This was echoed in the city of Plattsburgh, New York, where the mayor banned the mining of Bitcoin due to a concern of electricity usage. The imposed moratorium of 18 months was given after it emerged that the Bitcoin operations were accounting for 10% of the city's usage [36].

5. Software Data (Interfaces, applications)

5.1 Software and the User

The basis of any software model is the user interface, referred to as the Graphical User Interface (GUI), and the background processing of data, communication with the server or other computers on the network. The GUI needs to have a user friendly approach that allows the user to interact with the system with ease. The principal purpose of any energy trading platform is the interaction between peers, i.e., principally energy suppliers to list the energy that they have available for sale, and the consumers to be able to purchase that energy. To achieve an optimal experience for the users of the software platform, the use of databases should allow the system to filter and analyse users' requirements, and ultimately the result should allow the system to provide effectiveness and uncertainty whilst reducing transaction costs and providing transparency [37].

Consumer and prosumer apprehension must be addressed on certifying that energy can be bought, sold and payment can be received. This must be achieved through the usability of the software, with a building of trust [34].

6. Data

A significant part of the discussion about energy efficiency relies on energy digitalisation in order to provide the necessary means for intelligent and efficient operation and management [38]. By properly extracting and exploring the data present in the energy sector - whatever the infrastructure level - it will be possible to boost energy efficiency to a whole new level.

The access to the data and its correct use (always compliant with GDPR or any other regulations and policies) is at the core of the P2P scheme no matter if it concerns automation, connectivity, regulation or the empowerment of consumers/prosumers and several other stakeholders.

Although systems (hardware and software) vary enormously throughout the di verse types of implementations [39] (in what concerns diverse technologies, regulations, standardisation efforts or the lack of it, and so on), the concept of an efficient bi-directional communication [40] is mandatory to guarantee interoperability.

One of the most important issues for Peer-to-Peer is exactly the integration of the data in a way that can support innovative systems [8] and all sorts of energy community sharing and trading [5,8]. Tables 1, 2 and 3 are only a few examples of how diverse the energy data can be: Internet of Things (IoT) temperature readings, Photovoltaic (PV) readings and data for a district heating system substation operation (natural gas as primary fuel).

Standardisation of such diverse energy system and technologies is in its initial steps - if any. Therefore, the process of integration of these data sources in a coherent and usable way must be addressed properly. To tackle this challenge, the development of an ontology-based standardisation initiative can be an important action to foment data integration and, on a higher level, contribute to new regulations and policies.

6.1 Ontology

The devices participating in P2P implementation need to share a common structure of data communication to allow users (consumers and/or prosumers, regulators, etc.) and systems to share valuable information that will support operation, performance, trade, pricing and so on.

An Ontology can be a powerful tool [39,41] to deal with these challenges. The work of [42] suggests an ontology framework (Figure 1) to analyse and develop a standardisation effort of distinct components found in a P2P system, defining key concepts to interconnect systems by suggesting a neutral language to integrate such components. An example of the application of this ontology can be seen in a use case detailed in the following subsection.

6.2 Use case

The aforementioned ontology is part of the Cooperative ENergy Trading System (CENTS) project – a project coordinated by the International Energy Research Centre (IERC) and in partnership with industry experts, such as mSemicon [43], Community Power [44] and the research centres of University College Cork (UCC) [45], National University of Ireland Galway (NUIG) [46] and Technological University Dublin (TUD) [47].

CENTS is a platform for the electricity sector to connect users (consumers, producers and prosumers) and communities which are empowered with the infrastructure to generate their own electricity, earn from the surplus of electricity-production, and finally, contribute to decarbonisation policies in their homes and communities.

The use of this ontology scheme backed the work of defining how the sensors and IoT devices – PV readings, energy storage (battery status), temperature, and any other meters and sensors in general – could be integrated into the CENTS platform. By doing so, the ontology makes important contributions to the development of a data *"backbone"* that will be the base for energy trading and user empowerment.

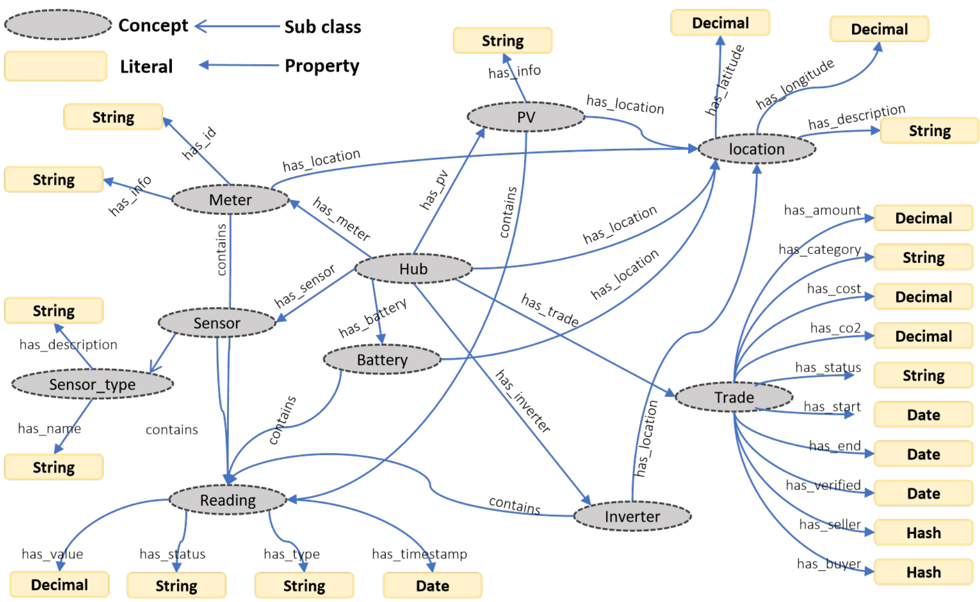

Figure 1 : An ontology-based data integration and standardisation scheme to tackle diverse data sources and formats [42].

id	room id	date	temp	in/out
unique reading IDs	location	date/time	readings	inside or outside
export.temp_log_196134_bd201015	Room Admin	08-12-2018 09:30	29	In
export.temp_log_196131_7bca51bc	Room Admin	08-12-2018 09:30	29	In
export.temp_log_196127_522915e3	Room Admin	08-12-2018 09:29	41	Out
export.temp_log_196128_be0919cf	Room Admin	08-12-2018 09:29	41	Out

Table 1: IoT temperature sample data [48]. Temperature readings on enterprise building room, both inside and outside, recorded at random intervals (one sample per second).

Provider	Date	Size DC	Zip Code	Utility	Manufacturer	Efficiency	Loading Rt
Arkansas State Energy Office	29/04/2010	2.016	71953	SWEPCO	Sharp	0.142430578	1.178947368
CA_CPUC	06/12/2019	8.88	95762	Pacific Gas and Electric	LG Electronics Inc.	0.221122586	1.113661945
CA_CPUC	07/11/2018	6.7	95409	Pacific Gas and Electric	LG Electronics Inc.	0.203189899	1.108170691

Table 2 : National Renewable Energy Laboratory, Department of Energy's Open Energy Data Initiative (OEDI) [49]. The dataset consists of 1 million Solar Cell Systems along with 78 columns of information on each system.

datum	*tsp*	*tsr*	*tns*	*tps*	*tnp*	*tpp*	*e*	*dt*	*qizm*
2/10/2017 9:00	5	47	46	42	84.5	43.1	67.499	4	179
2/10/2017 10:00	5	47	48	41	81	43.2	67.678	7	167
2/10/2017 11:00	5	47	46	41	77.5	43.1	67.845	5	185
2/10/2017 12:00	5	47	46	41	75.2	43	68.03	5	181
2/10/2017 13:00	6	46	50	41	80.5	44.1	68.211	9	
2/10/2017 15:00	6	46	46	41	79.5	42.2	68.564	5	179
2/10/2017 16:00	5	47	48	41	81.3	44	68.743	7	176

2/10/2017 17:00	5	47	47	41	83.8	42.7	68.919	6	196
2/10/2017 18:00	4	48	48	43	83.2	43.5	69.115	5	176
2/10/2017 19:00	4	48	48	42	82.8	43.1	69.291	6	185
2/10/2017 20:00	4	48	48	43	81.8	43.5	69.476	5	136

Table 3 : Historical data for District Heating System substation operation for 3 seasons [50]. The dataset includes: Outside air temperature (C, tsp), Water temperature in the secondary supply line (C, tns), Water temperature in the secondary return line (C, tp tps) and Heat energy transmitted (Kw, qizm).

7. P2P

Peer to peer systems in networking terms can be defined as a collection of links that connect the underlying nodes at the application layer and can be defined as a single overlay or multi-overlay system, and these can be broken down into further subcategories [51].

7.1 P2P in energy trading

The first use of the peer to peer trade in the energy space occurred in 2016, when the New York microgrid allowed a resident to trade with a neighbour [52]. As the use of renewable energies grows, and the distributed networks develop, it is believed that peer 2 peer energy trading will also develop allowing for the monitoring of not only the power network, but the level of consumption too [30].

Advantages

Presently the main production of power is through centralized systems that can be subject to down time, due to varying reasons. A decentralised model allows for consumers to have a greater reliability of sources, due to their local occurrence nearer to a prosumer [53]. In areas where electricity supply could be intermittent, or experience blackouts due to weather issues, the decentralised model could be a solution to aiding continual supply of energy. Projects such as SOLShare [54] have created a P2P system for off the grid areas in Bangladesh and India [55]. Bangladesh may be the global leader in solar installations, but for many families, without solar installations, reliance on neighbours is the only availability of energy [56]. The ability to purchase electricity from other community members allows for all houses to be electrified, and eliminate energy poverty in these areas. P2P has also been seen as a solution to blackouts caused by catastrophic weather events in the USA.

Disadvantages

P2P can also cause an unfairness problem between participating users. It may also lead to less oversight of data being handled which may impact on data privacy and may cause a GDPR breach.

8. Examination of existing projects

The following is a subset of the entire list of projects that were reviewed during this research, the full list is contained within the appendix. The authors reviewed over 150 projects and trials and reduced this to the following for further, more detailed analysis.

Selection of established and new worldwide projects

Piclo [57]

Introduced in 2015 in the UK, Piclo was the first online P2P electricity trading platform. It is the UK's leading software program for democratization and decentralized electricity market [31]. It was a collaboration between "Open Utility", an innovative technological company, and "Good Energy", a renewable energy supplier, where consumers were enabled to purchase electricity directly from the producers of renewable energy [58].

In the peer-to-peer energy trading system, smart meter data, producer/generator pricing and information about consumer preferences were used to match demand and supply of electricity energy half hourly [31]. This method enabled registered consumers to choose the producers/generators that they wanted to purchase from. The matching of consumers and producers involves factors such as preferences, prioritized producers/generators, location, cost and ownership, as well as various data visualizations and analytics [58]. Good Energy plays an important role in Piclo to maintain a balance in the marketplace by providing essential information such as contracts, billing and smart meter data [58].

Vandebron [66]

Developed in The Netherlands, Vandebron is an online energy platform that allows energy consumers and prosumers to purchase electricity directly from independent producers [58]. The platform brings together supply and demand of energy and links the producers of sustainable energy to households. The energy marketplace provides consumers with a selection of energy producers such as solar, wind and bioenergy.

Elecbay [67]

This platform, designed by Cardiff University (UK), allows users to forecast their own energy generation vs consumption, and create schedules for the purchase and selling of electricity. It is believed that is it one of the first platforms for LV distribution networks energy trading, where trading occurs between consumers, prosumers and energy suppliers [68]. In the case of a seller unable to generate the promised scheduled trade value, a penalty will be set, and the seller will have to fulfil their contract by purchasing power from another seller.

Smile [63]

Smile is a project that has been demonstrated on three pilot islands, with various methods of renewable generation. PowerShare was the platform that was developed, which was a mobile app that connects to the Energy Trading Management system, that allows users to monitor trade and consumption [34].

Company/Project	Type	Country / Area
HashCash [59]	Using smart contracts to trade solar energy	Germany
Omega Grid [60]	Solar generation, with interest in EV charging	USA
Pebbles [61]	Optimizing virtual power plants, with cloud based services to develop a local P2P blockchain solution	Germany
PETCON [62]	Hybrid vehicles in smart grids using P2P blockchain	USA
PICLO [57]	Britain's first peer to peer renewable energy trading platform	UK
Smile [63]	Various energy sources	3 European Islands
SolarShare [64]	Singapore's first solar trading platform	Singapore
SolShare [54]	Allowing rural communities to utilize solar through P2P	Bangladesh
SonnenCommunity [65]	Subscription based service, using solar and battery storage	Germany, Austria, Switzerland and Italy
TransActive Grid [53]	P2P community project - LO3 pilot project - The Brooklyn Microgrid	USA
Vandebron [66]	Sells renewable energy, and also natural gas	Netherlands

Table 4 : P2P projects and companies

Energy Web [69]

Launched in 2019, the Energy web is a non-profit organisation focusing on building a core infrastructure with the use of open-source and decentralised technologies. A blockchain system supported by international companies, its has acquired 25 validators, over 17 countries, within its first year, and is working with these international companies to develop its tools and systems. It is solely developed as a platform provider, allowing for it to be the central point of a energy-sector community [70].

8.1 Project shortcomings and regulation

Yehola [71] began as a project in 2012 to educate and encourage solar usage between communities. As the project developed, it became a Solar Sharing Network with a subscription web based platform marketplace that allowed non solar panel users to also buy green energy, but due to lack of finance and regulatory instability Yehola ceased trading in 2015.

Regulatory capping on renewable fuels around the world differs between countries, and regions, but it provides barriers to the generation and use of renewable energies.

In the USA net metering caps, differing from state to state, can limit the solar energy producers' returns on selling excess energy to the grid, tax breaks or the number of installations the state will allow [72]. Such inhibitions are stalling the growth of the renewable energy market, especially solar, which can be easily installed for many users, but states such as South Carolina see the renewable energy market as a way to deliver resilient power. For many years South Carolina has relied on fossil fuel generators to provide power through black outs caused by extreme weather events, but as these events are on the rise with climate change, the elected officials are looking at other methods of providing backup power [73]. This resulted in the publication of the "Energy Freedom Act" which requires utilities to explore solar plus storage generation assets and lift the 2% net metering cap [74].

Germany, a country that is seen to be a forerunner in renewable energy generation, removed solar generation caps in 2020, and minimum distancing with regard to onshore wind turbines, after the country saw a drop in 2019 in wind energy generation, mainly due to regulatory issues [75]. It is hoped that this change, i.e. the shift of the political strategy, will assist Germany in meeting its 2030 30% renewable target. In Japan consumers can only purchase electricity from a retail power company, so to enable the development of renewable energy and blockchain, differing retail power companies have partnered with different projects to trial platforms. PowerLedger have partnered with electricity retailer eRex [76], along with other partnerships electricity retail partners including LO3, Ricoh, and the recent collaboration of Mitsubishi Electric and Tokyo Institute of Technology to develop a system that they can commercialise at the earliest possible opportunity [77].

9. Conclusions and Discussion

As mentioned, Germany is a forerunner in renewable energy adoption in Europe, therefore it would not be surprising to say that Germany is also a forerunner in adopting blockchain. September 2019 saw a commitment to the use of blockchain, across various industries. The adoption of the national blockchain plan has seen development of regulatory measures crossing various aspects of the blockchain plan. In the energy space a dedicated "Future Energy Lab" was developed and launched in August 2020, as a project by the German Energy Agency, to serve as a networking center and a point of contact [78].

Hardware is a critical part of any P2P/TE/CSC project enabling the transmission of data and the control of necessary equipment. The basic hardware elements of P2P projects are consistent across most of the P2P/TE/CSC projects analysed, although the setup and design parameters of the different hardware components vary significantly. The meters and sensors needed for the projects to function can be positioned and set up in a multitude of configurations and to provide varying amounts of data. Similarly, types of controllers and actuators in the system can vary between rule based to Artificial Intelligence (AI) based, which rely on ever increasing amounts of data.

Differences in sensor hardware precision and/or accuracy- while monitoring similar phenomena- must be addressed properly. The sensors can duplicate each other or just have partial overlap (competitive measurements), or be combined to create a more accurate observation of a phenomenon (cooperative measurements). Nevertheless, to achieve these results, the sensor outputs must be integrated - and eventually rectify and/or recombine the data if they disagree.

Usually, the integration of sensor data is done by algorithms with different levels of complexity to compile coherent results. Additionally, the algorithm must be able to manage vast amounts of data in order to condense the data into useful and manageable results.

Software for any P2P/TE/CSC project can be classified as critical, as it is the enabler for the system to allow the users/actors throughout the system to interact with it and allows for the analysis of metrics, forecasting, as well as many other aspects to be explored in the system. This software interface can take many constructs and be developed in many different ways, such as through a mobile or web application, or simply as an interaction enabled interface on a smart meter or device. As with any system, the software is respective of the system design, moulded with the users' requirements and can be seen as to be only relative to that project or solution. Thus, even though we have discussed various projects in this review, the software developed for each can be defined as only relevant to the project that it describes.

Therefore, little foresight is given into software solutions for the varying projects, with more emphasis given toward the physical network or project motivation.

Data is a valuable part of any system as it allows the establishment of baselines, benchmarks, facts and statistics. In a P2P/TE/CSC model, data is often gathered through various sources including hardware (such as smart meters, actuators, sensors), and via software tools. Large volumes of data are being collected continuously from these hardware and software systems. Data is widely available in many formats, however, this data is found to be largely unstructured, which is a challenge we face in decentralised models.

There are many opportunities that exist for standardisation in P2P/TE/CSC. By focusing on archetypes as the root of these models, branching out to identify recommended hardware, software and data ontologies for these archetypes will prove beneficial to future trials and implementation of the models.

As stated in the introduction, this paper has outlined the breadth and depth of the hardware, software and data related issues of current research and practice in decentralised energy generation and use models, so as to help signpost and navigate the wide and varied aspects of this domain. In terms of the further outlook, this work will continue to focus on helping the Peer-to-Peer (P2P), Transactive Energy (TE), Community Self-Consumption (CSC) researchers and practitioners to, on the one hand, better appreciate the complexities and interactions across the hardware, software and data aspects discussed above, and, on the other hand, to practically replicate successful solutions for businesses. To this end, we plan to undertake a number of case studies of cutting edge P2P, TE, and CSC research and practice pilots and projects. Each case study will present the specific hardware, software and data solutions, along with the relevant context for their successful operation and adoption as well as the related research and practical challenges. Through this work we aim to both foster further research on practical-driven challenges and facilitate example-based practical adoption of these energy generation and use models.

Conflicts of Interest

The authors of this paper are currently involved in the Cooperative Energy Trading System (CENTS) project and have NO agreements with study sponsors, both for-profit and non-profit, that interfere with authors' access to all of the study's data or that interfere with their ability to analyze and interpret the data and to prepare and publish manuscripts independently when and where they choose. Proper acknowledgement of support and funding is clearly stated in Section Acknowledgements, and the authors also declare NO conflict of interests that could inappropriately influence or bias the work presented in this paper.

Author contributions

Conceptualization, B.O. and F.S.; methodology, B.O.; validation, B.O., B.H., V.H., R.C. and P.L.; investigation, B.O., F.S., E.O., F.T., K.M. and R.C.; resources, B.O. and F.S.; writing—original draft preparation, B.O., F.S., E.O., F.T. and K.M.; writing—review and editing, B.O., F.S., E.O., F.T., K.M., B.H., V.H., R.C. and P.L.; visualization, F.S.; supervision, B.O. and F.S.; project administration, B.O. and F.S.; funding acquisition, B.O. All authors have read and agreed to the published version of the manuscript.

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11. Appendix

Acronym	Meaning
CENTS	Cooperative ENergy Trading System
CSC	Community Self-Consumption
EU	European Union
GDPR	General Data Protection Regulation
GUI	Graphical User Interface
HEMS	Home Energy Management System
IEA	International Energy Agency
IEEE	Institute for Electrical and Electronic Engineers
IERC	International Energy Research Centre
IoT	Internet of Things
MU	Merging Unit
NUIG	National University of Ireland Galway
P2P	Peer-to-Peer
PEV	Plug-In Electric Vehicle
PMU	Phasor Measure Unit
PV	Photovoltaic
ROCOF	Rate of Change of Frequency
TE	Transactive Energy
TUD	Technological University Dublin
UCC	University College Cork
Users TCP	User-Centred Energy Systems Technology Collaboration Programme
UTC	Coordinated Universal Time
WSAN	Wireless Sensor and Actuator Network

Project name	Website
4New Cryptocurrencies	https://www.facebook.com/4newcoin/
Alliander (Alva)	https://2019.jaarverslag.alliander.com/ http://blockchain.alliander.com/map
Alliander & Spectral Energy (Jouliette at De Ceuvel)	https://spectral.energy/projects/
ampcontrol - Alliander (Charge Ledger)	https://www.ampcontrol.io/
Assetron Energy Cryptocurrencies / ASTRNENERGY	https://twitter.com/ https://astrn.com/
Bankymoon Metering	
BAS Nederland Metering	
BCDC (Blockchain Development Company) Cryptocurrencies	
BCPG Group Decentralised	
Bettergy	https://www.bettergy.es/tecnologia/lineas-de-investigacion/
BEYOND	https://beyond-project.eu
Bittwatt Decentralised	
BLOC (EnergyBlock & Community Power)	
Blockchain Energy	https://blockchainenergyinc.com
Blockchain Futures Lab	
Blockchain Research Lab	
BlockLab	
Bouygues Immobilier & Stratumn	
Brookyln Microgrid	
BTL	
Car eWallet	
CarbonX	
Centrica	
CENTS	http://centsproject.ie
CGI & Eneco	
Clearwatts	
Community First! Village	https://mlf.org/community-first/
Conjoule	
CoSol	
DAISEE	
Dajie	
DAO IPCI (MITO)	
Department of Energy, US IoT, smart devices, automation & asset management	
Department of Energy, US Metering, billing & security	
Divvi	
Dooak	
Drift	
Drift	https://www.joindrift.com/
EcoCoin	

ElectriCChain (SolarCoin)	
Electrify.Asia	https://www.electrify.asia/marketplace/
Electron	https://electron.net/
Electron Grid management	
Electron Metering	
Elegant Metering	
eMotorwerks	
Empower	http://empowerh2020.eu/the-project/
Endesa Energia	
Enerchain	https://www.ponton.de/enerchain-1-0-is-live/ https://www.ponton.de/enerchain-p2p-trading-project/
Enercity	
Eneres	
Energi Mine	
Energo Labs	
Energo Labs	
Energy Bazaar	
Energy Collective	https://weou.org/energy-collective/
EnergyWeb Foundation	
Energy-Blockchain Lab & IBM	
Energy21 & Stedin	
EnerPort	
Enervalis (NRGCoin)	
Engie	
EnLedger	
Envion	
EU Blockchain Observatory	
Eurelectric (Blockchain Discussion Platform)	
EverGreenCoin	
Everty	
Evolve Power	
Farad	
Filament Grid management	
Filament IoT, smart devices	
Fortum	
Freeelio (AdptEVE)	
Green EnergyWallet	
Green Running (Verv)	
Greeneum	
Grid Singularity	
Grid+	https://gridplus.io/
Gridwiz	https://www.gridwiz.com/en/solutions/e-mobility
Grünstromjeton	
Hive Power	

HydroMiner	
IBM & Linux Foundation (Hyperledger)	
ImpactPPA	
Innogy Motionwerk (Share & Charge)	
Intrinsic ID & Guardtime	
Inuk	
Kansai Electric	https://www.kepco.co.jp https://coingeek.com/kansai-electric-leads-study-blockchain-use-distributed-electric-supply/
KEPCO	https://www.zdnet.com/article/south-korea-to-trial-blockchain-electricity-market-for-consumers/
Level10	https://leveltenenergy.com
Lichtblick Swarm Energy	https://www.lichtblick.de/
Lition	https://lition.io/
LO3Energy	https://lo3energy.com/
Local-e	
Lumenaza	
M-PAYG	
Marubeni (Coincheck Denki)	
ME SolShare	https://me-solshare.com/
MiFIC	
MyBit	
Nasdaq New York Linq	
NOBEL	https://bit.ly/3nTC3Lj
NRGcoin	https://nrgcoin.org/
Oli	
OMEGAGrid	
OneUp	
OurPower (CEDISON)	
Oursolargrid & ITP	
Oxygen Initiative	
P2P-SmartTest	https://www.p2psmartest-h2020.eu/
P2P3M	https://p2pconnecting.wordpress.com/
Peebles / Siemens	https://pebbles-projekt.de/en/ https://sie.ag/3f1MEQe
PeerEnergyCloud	https://bit.ly/3vJB6bc
PetroBloq	
Piclo	https://piclo.energy/about#whitepaper
Platinum Energy Recovery	
PONTON (EnerChain)	
Poseidon	
Power Ledger	
Power-ID	
PROSUME	
PRTI	

Pylon Network	
Restart Energy	
Slock.it	
Smart Watts	https://www.psi-energymarkets.de/en/company/research-and-development/smart-watts/
Solar bankers	
SolarChange (SolarCoin)	
SOLshare	
SonnenCommunity	https://sonnengroup.com/sonnencommunity/
SP Energy Networks, SSEN, SP Distribution, SP Manweb &	
UK Power Networks	
Spectral Energy	
State Grid Corp of China	http://www.sgcc.com.cn/
Street2Grid	https://gtr.ukri.org/projects?ref=EP%2FS001778%2F1
StromDAO	
SunChain	
SunContract	
SwytchX	https://swytch.io/
Tavrida Electric	
Tennet & Sonnen	
Tennet & Vandenbron	
The Sun Exchange	
ToBlockChain	
toomuch.energy	
TransActive Grid	
VAKT & partners (including BP, Shell & Statoil)	http://transactivegrid.net/ (NOT AVAILABLE)
Vandebron	https://vandebron.nl/
Vattenfall (Powerpeers)	
Vector Energy (EcoChain)	
Veridium Labs	
Volts Markets	
Wanxiang	
WePower	
Wien Energie	
Wirepas	
Wuppertal Stadtwerke (Tal. Markt)	
XinFin	
Yeloha Mosaic	https://www.linkedin.com/pulse/lights-out-yeloha-why-we-shut-down-solar-sharing-network-rosner/