energies

IMPACT FACTOR 3.0

CITESCORE 6.2

Article

Balancing Usage Profiles and Benefitting End Users through Blockchain Based Local Energy Trading: A German Case Study

Liaqat Ali, M. Imran Azim, Nabin B. Ojha, Jan Peters, Vivek Bhandari, Anand Menon, Vinod Tiwari, Jemma Green and S.M. Muyeen

Special Issue
Sustainable Energy Transition, Utilization and Management to Achieve SDG 7

Edited by
Dr. GM Shafiullah and Dr. Umashankar Subramaniam

MDPI

https://doi.org/10.3390/en16176315

energies

MDPI

Article

Balancing Usage Profiles and Benefitting End Users through Blockchain Based Local Energy Trading: A German Case Study

Liaqat Ali [1,*], M. Imran Azim [1], Nabin B. Ojha [1], Jan Peters [1], Vivek Bhandari [1], Anand Menon [1], Vinod Tiwari [1], Jemma Green [1] and S.M. Muyeen [2,*]

[1] Powerledger, Level 2, The Palace, 108 St George's Terrace, Perth, WA-6000, Australia
[2] Department of Electrical Engineering, Qatar University, Doha 2713, Qatar
* Correspondence: la@powerledger.io (L.A.); sm.muyeen@qu.edu.qa (S.M.M.)

Abstract: The electricity market has increasingly played a significant role in ensuring the smooth operation of the power grid. The latest incarnation of the electricity market follows a bottom-up paradigm, rather than a top-down one, and aims to provide flexibility services to the power grid. The blockchain-based local energy market (LEM) is one such bottom-up market paradigm. It essentially enables consumers and prosumers (those who can generate power locally) within a defined power network topology to trade renewable energy amongst each other in a peer-to-peer (P2P) fashion using blockchain technology. This paper presents the development of such a P2P trading-facilitated LEM and the analysis of the proposed blockchain-based LEM by means of a case study using actual German residential customer data. The performance of the proposed LEM is also compared with that of BAU, in which power is traded via time-of-use (ToU) and feed-in-tariff (FiT) rates. The comparative results demonstrate: (1) the participants' bill savings; (2) mitigation of the power grid's export and import; (3) no/minimal variations in the margins of energy suppliers and system operators; and (4) cost comparison of Ethereum versus Polygon blockchain, thus emphasising the domineering performance of the developed P2P trading-based LEM mechanism.

Keywords: local energy market; peer-to-peer; blockchain; power grid; energy supplier; system operator; electricity cost reduction

check for updates

Citation: Ali, L.; Azim, M.I.; Ojha, N.B.; Peters, J.; Bhandari, V.; Menon, A.; Tiwari, V.; Green, J.; Muyeen, S.M. Balancing Usage Profiles and Benefitting End Users through Blockchain Based Local Energy Trading: A German Case Study. *Energies* **2023**, *16*, 6315. https://doi.org/10.3390/en16176315

Academic Editors: GM Shafiullah and Umashankar Subramaniam

Received: 23 March 2023
Revised: 1 May 2023
Accepted: 9 May 2023
Published: 30 August 2023

1. Introduction

In recent years, the notion of a local energy market (LEM) has gained substantial momentum at the residential level. A LEM is basically a sub-energy market that operates to provide residential customers with competent local energy trading and management services [1]. The nature of LEM operations makes it highly feasible to comply with both economic and technical requirements while incorporating clean energy into a physical energy network [2]. Characteristically, a LEM is dissimilar to other available techniques, such as distributed resource management systems (DERMS) and advanced distribution management systems (ADMS). This is because LEM operation is exclusively determined by the participating residential customers, who could be consumers with or without distributed energy resources (DERs), which commonly include solar photovoltaic (PV) systems and battery energy storage systems (BESSs). Consumers with DERs are also often designated as prosumers [3].

Peer-to-peer (P2P) is one of the most underlined aspects of a LEM that enables participants (both prosumers and consumers) to function as independent energy traders and attain remarkable monetary rewards following a decentralised market structure [4]. The operative negotiations between LEM participants and protected financial settlements can be organised on an automated distributed service platform called blockchain [5]. Typically, a LEM not only secures the financial gains of participants and other stakeholders, including energy suppliers, distribution system operators (DSOs), and transmission system operators

(TSOs), but also abides by the physical constraints that the accommodated energy network has to be compatible with [6]. In other words, while financial decisions are arranged in the LEM, the actual energy dispatch is also systematised, respecting the technical constraints of the energy network [7]. In general, P2P trading could fall into three categories in a LEM: decentralised, community-driven, and hybrid [8]. The engagement of any centralised entity is not permitted in a decentralised P2P market, but a community-driven P2P market is maintained by a community manager. In contrast, while the compatibility of the technical constraints is taken care of by an authorised entity, the financial settlements are conducted independently in a hybrid P2P market [9].

Nevertheless, while several benefits are envisaged for LEMs as they possess the P2P trading feature, a number of potential challenges are also associated with the framework. These include guaranteed financial benefits for the participants compared with business-as-usual (BAU), whereby energy is bought and sold at the time-of-use (ToU) and feed-in-tariff (FiT) rates, respectively [10], conspicuously managing power grid export and import to relieve the energy network from congestion during peak operational periods [11], confirmed margins for stakeholders to fend off financial losses [12], and physical network integrity-ensured performance [13]. To deal with these challenges, numerous studies have been conducted over the past few years. For instance, the authors in [14] analysed the attitudes, behaviours, and subjective norms of the LEM participants and designed a P2P trading-empowered LEM that prioritised the preferences of LEM participants. They were also directed to decide on their trading partners, periods, and trading contracts by themselves in a competitive environment in [15]. Furthermore, options were granted to trade either as a member of a group or separately in [16]. The importance of efficacious P2P decision-making was emphasised in [17]. Moreover, few factors were reported in [18] that predominantly influenced the P2P decision-making, e.g., mutual trusts, climate change, political orientation, and place attachment.

The minimisation of energy usage costs was labelled as the principal key driver in [19] when it came to motivating participants to join the LEM and take P2P strategic decisions. This was further accentuated by the authors in [20] and demonstrated clearly how their formulated P2P decisions impacted the energy costs of the LEM participants. In fact, in [21], LEM participants were guided to exchange energy at a price higher than the FiT price, but lower than the ToU price. The purpose was to incentivise both LEM sellers (participants who possessed more DER energy than demand) and LEM buyers (participants who possessed more demand than DER energy). The scope of BESS in reducing the energy bills of LEM participants to a greater extent was also analysed in [22]. The idea of lessening the energy expenses of LEM participants by rescheduling their behaviours was brought up by the authors in [23]. The performance of the LEM was also examined in [24] from a social point of view to raise the value of the LEM in society. A comparative study was carried out in [25] to articulate the economic viability of a networked LEM.

Some recent studies also focused on the possibility of incorporating energy stakeholders' interests into the LEM mechanism while P2P transactions are frequently executed. For example, to curtail the peak demand of the LEM participants, the authors in [26] proposed a power grid-engaged P2P trading scheme that could function as a prospective alternative to the conventional energy demand response. The exercise of P2P trading among LEM participants was further reported on in [27] to match the local supply with the local demand. These participants were also rewarded in [28] for assisting the DSO or TSO in balancing energy in a local community. The uncertainty associated with local energy supply was considered in [29] while P2P transactions were performed. Distributed P2P trading schemes considering physical network constraints and power losses were modelled in [30] and [31], respectively. Additionally, an integrated participant–DSO/TSO framework was proposed in [32] that fruitfully achieved safe LEM operation. The charge for using the energy network was added to the financial settlement of P2P trading in [33] to derive the portion of the DSO or TSO. The necessity of involving energy suppliers in a practical LEM was acknowledged in [34]. Their role was further justified in [3]. Additionally, how aggregated prosumers could be transformed into potential energy suppliers in the future was introduced in [35].

Although several market clearing approaches, such as rule-based mechanism [36], game theory [37], double auction [38], iterative auction [39], and alternating direction method of multipliers [40], have been tested in the existing literature, the uses of linear programming (LP)- and mixed integer linear programming (MILP)-assisted constraint optimisation are immensely noticeable without a loss of generality in formulating a LEM by satisfying both market and technical constraints. The LP technique was adopted by the authors in [41,42] to facilitate LEM flexibilities and organise effective LEM scheduling, respectively. It was utilised further in [43] to design the P2P contracts between LEM participants. On the other hand, the application of the MILP method was evident in [44–48] for analysing electricity price components, optimising locally produced energy, maintaining the uncertainty of local demand and supply, designing virtual bidding mechanisms, and cutting back the total energy supply expenditures, respectively. Additionally, this mechanism has been applied to handle the community-oriented P2P trading model [49], conduct home-to-home trading via P2P methodology [50], operate a hierarchical P2P energy management system [51], and finalise energy transactions with the energy supplier [52].

Certainly, the available literature lays the foundation to portray the beneficial facets of P2P trading in LEMs. What is missing is a combination of all the features of P2P trading that include the use of blockchain technology, financial gains for the LEM participants, power grid benefits, and margins for the energy suppliers and the DSO/TSO. To this end, this paper focuses on developing a blockchain-enabled LEM strategy that comprises all these features and also validates the LEM framework via a German case study. The case study model is based on Berlin, Germany, as shown in Figure 1, and open-access German residential data from [41,53] are used. The average (taken from 200 LEM participants) generation, consumption, and solar P2P output over the course of 24 h are also provided in Figure 2. Nonetheless, the core contributions of this paper are epitomised below:

- An overview is provided to help the reader understand the LEM network architecture and how blockchain can be included in the studied LEM system;
- A P2P trading framework is proposed to organise bilateral transactions in the LEM, considering financial, physical, and BESS constraints;
- A case study is carried out, based on German data, involving participants and stakeholders to assess the developed LEM's performance;
- Extensive simulation results are provided to demonstrate the benefits for all LEM participants and stakeholders. Further, cost comparison is performed to select the most suitable blockchain to accommodate the modelled LEM.

Figure 1. Map of Berlin, Germany.

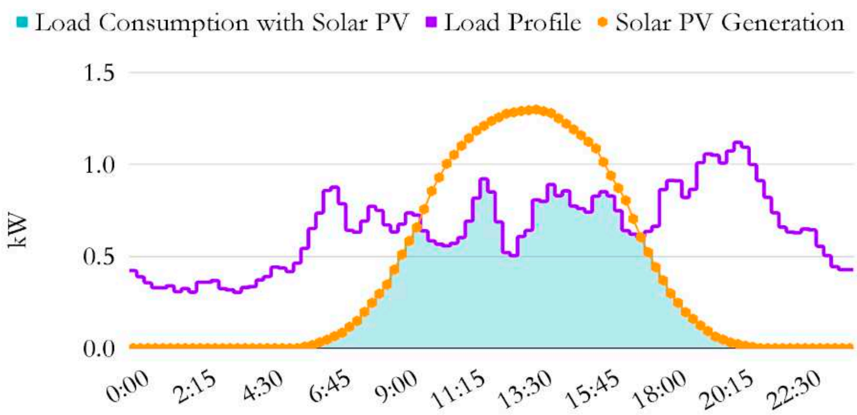

Figure 2. Average load profiles and solar PV output.

The remainder of this paper is organised as follows. Section 2 provides a brief overview of the LEM model and blockchain integration. Section 3 formulates the methodology to solve the proposed LEM design, respecting both market and technical constraints. A case study with a comparative analysis of the results is provided in Section 4. Finally, concluding remarks are presented in Section 5.

2. LEM Network Architecture

Figure 3 displays the LEM network architecture, which comprises 200 participants in total. Among them, 120 are consumers, 40 are prosumers with solar PV systems, and 40 are prosumers with solar PV systems and BESSs. Prosumers are assumed to be equipped with 6 kW of solar PV system capacity on average, while 50% of them (20% of the total LEM participants) have a 3.3 kW/12.5 kWh BESS size, on average. In this study, two energy suppliers [54,55] are considered from Berlin, Germany. Energy Supplier-1 has 100 participants as customers in total, including 50 consumers, 25 prosumers with solar PV systems, and 25 prosumers with solar PV systems and BESSs. In contrast, Energy Supplier-2 has 100 participants as customers in total, consisting of 70 consumers, 15 prosumers with solar PV systems, and 15 prosumers with solar PV systems and BESSs.

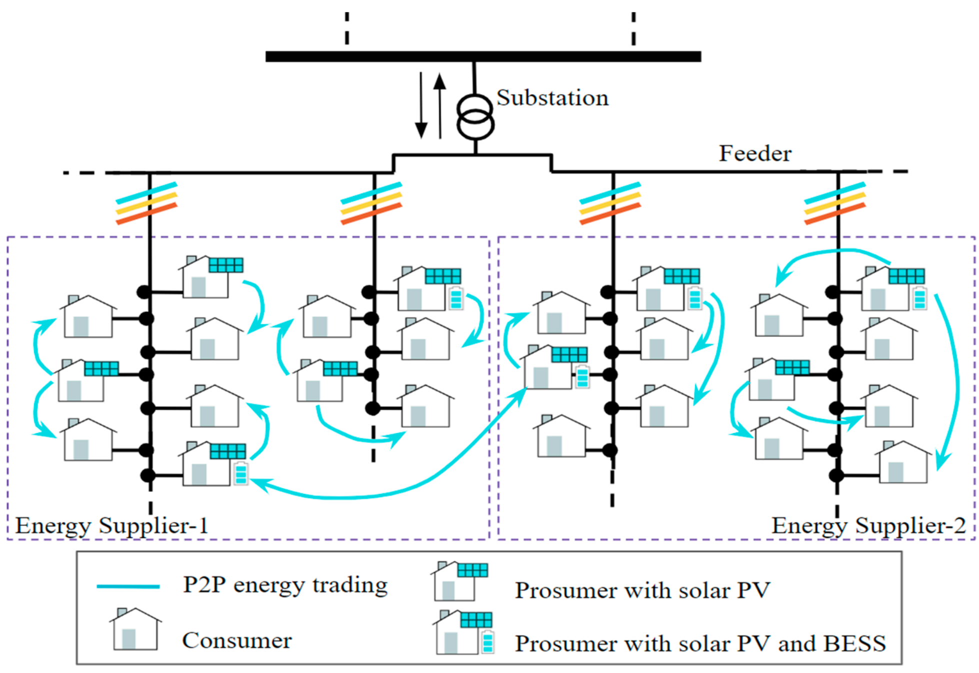

Figure 3. LEM network architecture.

Figure 4a,b illustrate the energy flow, internet-of-things (IoT) signal flow, and cash flow among all participants and stakeholders in the blockchain-based LEM platform. All LEM participants are connected to the LEM platform and send and receive IoT signals, as shown in Figure 4a. The LEM platform also facilitates participants placing their trading bids for P2P energy trading in the LEM. The physical energy flows in the LEM network are caused by the export of prosumers and the import of consumers and are considered to be operated by the DSO/TSO [56]. The cash flow among energy suppliers and other stakeholders is shown in Figure 4b.

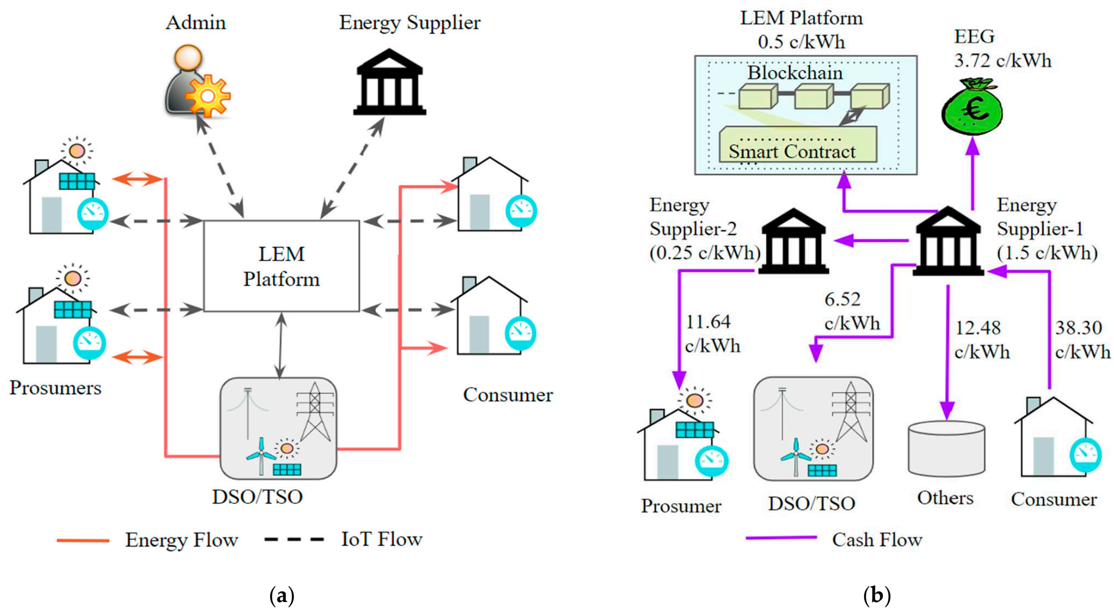

Figure 4. (**a**) P2P energy flow and IoT signals in the LEM, and (**b**) cash flow in the LEM.

Table 1 presents the comparative rates of the daily supply, network, energy suppliers, Erneuerbare-Energien-Gesetz (EEG), LEM transaction fee, energy price, and other taxes and levies in the case of both BAU and P2P energy trading for both energy suppliers. While the rates of the daily supply, EEG, DSO/TSO fees, and other taxes and levies were unvarying for both trading scenarios, the LEM transaction fee was only applied when P2P transactions occurred within the LEM. The energy price and P2P price, on the other hand, were different, as the LEM aimed to benefit the participants (both sellers and buyers) in comparison with the BAU. Further, the margins of energy suppliers increased slightly owing to the fact that they earnt their portions every time P2P transactions were executed in the LEM. In Sections 2.1 and 2.2, how blockchain technology is used in the LEM and how the fees of P2P transactions are measured, respectively, are explained.

Table 1. An example of the comparative rates between BAU and P2P.

	Energy Supplier-1 [57]		Energy Supplier-2 [58]	
Scenarios	**BAU (A)**	**LEM (B)**	**BAU (A)**	**LEM (B)**
Daily supply (c/day)	34.67	34.67	22.48	22.48
FiT (c/kWh) [59]	6.43	6.43	6.43	6.43
DSO/TSO (c/kWh) [60]	6.52	6.52	6.52	6.52
EEG (c/kWh) [61]	3.72	3.72	3.72	3.72
Other taxes and levies (c/kWh) [60]	12.48	12.48	12.48	12.48
Energy supplier—5% (c/kWh)	1.5	1.75	1.5	1.75
LEM transaction fee (c/kWh)	0	0.5	0	0.5
Energy/P2P (c/kWh)	9.03	6.56 to 7.61	13.17	6.56 to 11.64
Tariff	**33.25**	**31.53 to 32.59**	**39.08**	**33.22 to 38.30**

2.1. Blockchain Integration in the LEM

Blockchain is essentially a distributed database that is immutable, protected, and encrypted. Records of data and transactions are preserved chronologically in blocks and authenticated by common consensus procedures. Smart contracts, which represent the terms and conditions of contracts through computer codes, are used to electronically and automatically document such consensus mechanisms. These smart contracts are also stored in the blockchain database to secure immutability. With smart contracts, a variety of decentralised applications (dApps) can be created. Ethereum is one of the first blockchains that actually supports both smart contracts and dApps.

The LEM platform, based on blockchain, is also a dApp. Figure 5 depicts the Ethereum blockchain's integration into the LEM. All LEM prosumers and consumers are connected to the smart contract and blockchain through the LEM dApp, which encompasses the user interface (UI) and the web3 interface. While LEM prosumers' and consumers' bids are arranged with the help of the UI, the web3 interface connects that UI to the smart contract-driven blockchain database.

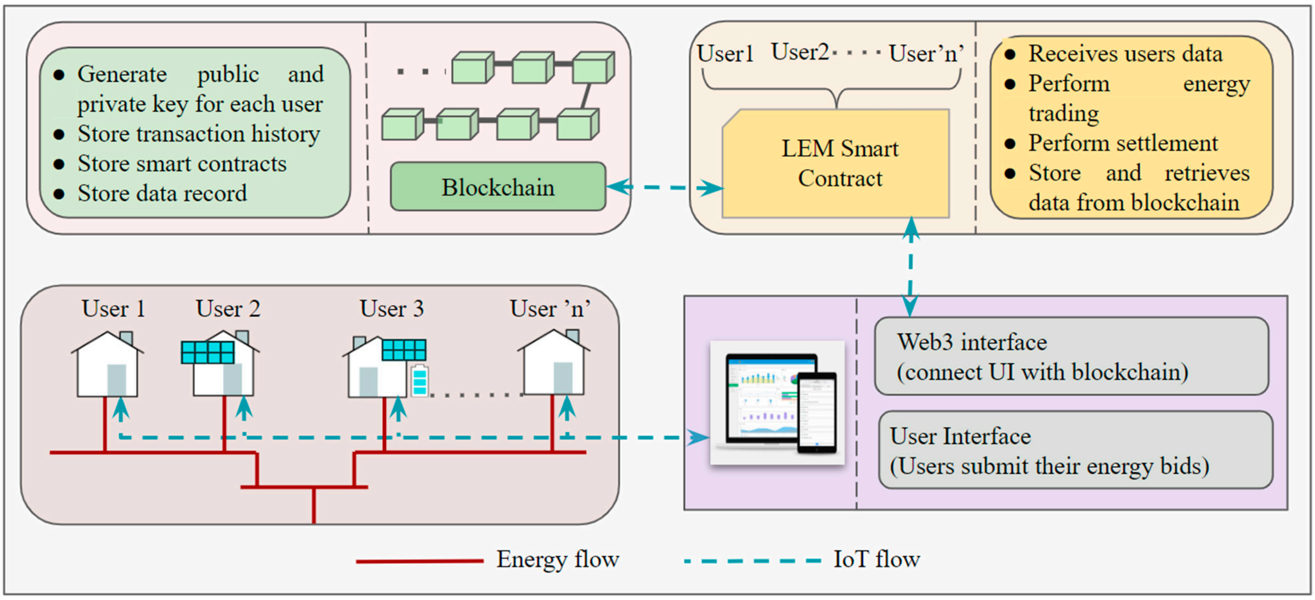

Figure 5. Blockchain technology integration in the considered LEM.

Smart contracts are self-executing computer programs that have the ability to automatically verify, enforce, and execute the terms of a contract. In the context of blockchain technology, smart contracts are used to automate and enforce the terms of transactions on the blockchain without the need for intermediaries. They can be programmed to trigger automatically when certain conditions are met, such as receiving payment or completing a specific task. Smart contracts increase transparency, efficiency, and security in transactions as they eliminate intermediaries and are decentralised, making them resistant to tampering and fraud. They are a vital element of blockchain technology that enable secure and automated transactions. A LEM smart contract, with regard to data processing of prosumers and consumers, P2P energy trading strategy and market clearing, billing settlement, and blockchain storage, is written and stored in the blockchain database. The blockchain platform generates a private key for each LEM participant and records all P2P transactions' data and history.

2.2. P2P Transactions Fee Using Blockchain

P2P data and transactions are validated on the blockchain-integrated LEM platform. All computers of the LEM participants, which are connected to the blockchain-integrated LEM network, provide their computational resources for the purpose of managing data integrity and immutability in the LEM network. LEM transaction fees are paid by the participants as incentives to the peers involved in verifying their transaction requests using an advanced algorithm. Nevertheless, gas units are utilised to measure the computation efforts exercised to validate LEM transactions. Each blockchain network has its own native cryptocurrency, and transaction fees are paid in that native cryptocurrency. ETH and MATIC are the native cryptocurrencies of the Ethereum and Polygon networks, and their prices in Euro are 1 ETH = 1139.86 Euro and 1 MATIC = 0.73 Euro [62]. The total transaction fee [63], symbolised by W, can be calculated in (1), where the blockchain native crypto price (Euro), gas amount, and gas price (WEI, where WEI is the smallest denomination of Ether (ETH), and 1 ETH = 1018 WEI) are denoted by c, g, and z, respectively.

$$W = c \times g \times z \times 10^{-18},$$

3. Formulated LEM Trading Methodology

This section explains the formulation of the proposed P2P trading in the LEM complying with respective market and technical constraints. The assumptions made to conduct P2P trading in the LEM are provided in Section 3.1. The main objective of the proposed LEM is provided in Section 3.2. Sections 3.3 and 3.4 demonstrate the derivation of the objective function and associable constraints, respectively.

3.1. Assumptions

The following assumptions are made to develop the P2P trading-facilitated LEM:

- Prosumers and consumers are located at the same distribution substation, but the trading partners can have different energy suppliers;
- Prosumers can participate in the LEM either as a seller or as a buyer, depending on their energy status. However, consumers can only purchase energy from the LEM and serve as buyers;
- Around 20% of prosumers are outfitted with the BESS to bring flexibility in the LEM;
- Excess solar PV energy is prioritised to sell first in the LEM via P2P, followed by the BESS-stored energy. Likewise, power demand is met in the first place, and then the BESS is charged;
- P2P trading takes place if the LEM selling price is higher than the FiT rate while the grid buy price is higher than the LEM buying price.

3.2. Objectives

- The foremost goals of the LEM model is to diminish the energy expenditure of all participants (both sellers and buyers) compared with BAU by enabling them to trade amongst each other via P2P. This can ensure the agile involvement of participants in the LEM;
- Other indispensable purposes are to cut down on grid export and import and escalate/retain the margins of other stakeholders, including energy suppliers and the DSO/TSO. This can encourage operators and stakeholders to join in the LEM trials and evaluate their overall economic gains.

3.3. Derivation of Objective Function

Let T be the set of LEM participants, in which the index of each participant is denoted by $t \in T$. As mentioned before, LEM allows each participant $t \in T$ to trade as either a seller $l \in L \subset T$ or a buyer $u \in U \subset T$ based on their energy availability at a given time instant $e \in E$, where L and U represent the sets of sellers and buyers, respectively. The proposed LEM maximises the profit and saving of each participating seller and buyer at each $e \in E$. If $D^{LEM}(l,e)$ and $D^{BAU}(l,e)$ indicate earnings through P2P and BAU, respectively, $D^{LEM}(u,e)$ and $D^{BAU}(u,e)$ refer to expenses through P2P and BAU; the objective function N can be formulated as follows:

$$N = max\Big\{\Big(D^{LEM}(l,e) - D^{BAU}(l,e)\Big) + \Big(D^{BAU}(u,e) - D^{LEM}(u,e)\Big)\Big\};\ \forall l \in L \subset T,\ \forall u \in U \subset T,\ \forall e \in E \tag{1}$$

where $\left(D^{LEM}(l,e) - D^{BAU}(l,e)\right)$ and $\left(D^{BAU}(u,e) - D^{LEM}(u,e)\right)$ imply the profit and savings of each LEM participant by acting as either a seller or a buyer at any time instant $e \in E$. Subject to: Financial, physical and BESS constraints as presented in (14)–(39).

3.3.1. Profit and Saving Evaluation

Let the solar PV power and load power of each LEM participant $t \in T$ at a given time instant $e \in E$ be $P^{SOL}(t,e)$ and $P^{LOAD}(t,e)$, respectively. Assume that around 20% of LEM participants possess BESSs. The BESSs can be charged in two ways: (1) from their own solar PV (self-charging) or (2) from the LEM (P2P charging). Similarly, it can be discouraged to either meet up its load power or to sell on the P2P market. The net power $P^{NET}(t,e)$ of each LEM participant $t \in T$ at a given time instant $e \in E$ can be determined as:

$$P^{NET}(t,e) = \left(P^{LOAD}(t,e) - P^{SOL}(t,e)\right) + \left(P^{S-CHAR}(t,e) - P^{S-DIS}(t,e)\right) + \left(P^{P-CHAR}(t,e) - P^{P-DIS}(t,e)\right);\ \forall t \in T,\ \forall e \in E \tag{2}$$

where $P^{S-CHAR}(t,e)$ and $P^{S-DIS}(t,e)$ symbolise the self-charged BESS power and self-discharged BESS power, respectively. P2P-charged BESS power and P2P-discharged BESS power are denoted by $P^{P-CHAR}(t,e)$ and $P^{P-DIS}(t,e)$, respectively. Note that BESSs cannot be charged and discharged at the same time. Additionally, for prosumers without BESSs and consumers, $P^{S-CHAR}(t,e) = 0$, $P^{S-DIS}(t,e) = 0$, $P^{P-CHAR}(t,e) = 0$, and $P^{P-DIS}(t,e) = 0$.

Excess power and unmet power for the LEM seller $l \in L$ and LEM buyer $u \in U$, where L and U are subsets of T, signified by $P^{LEM-EX}(l,e)$ and $P^{LEM-UN}(u,e)$, respectively, at a given time instant $e \in E$ are calculated as:

$$P^{LEM-EX}(l,e) = \Big(-P^{LOAD}(l,e) + P^{SOL}(l,e)\Big) + \Big(-P^{S-CHAR}(l,e)\Big) + \Big(P^{P-DIS}(l,e)\Big);\ \forall l \in L,\ \forall e \in E \tag{3}$$

$$P^{LEM-UN}(u,e) = \Big(P^{LOAD}(u,e) - P^{SOL}(u,e)\Big) + \Big(-P^{S-DIS}(u,e)\Big) + \Big(P^{P-CHAR}(u,e)\Big);\ \forall u \in U,\ \forall e \in E \tag{4}$$

Let $P^{LEM-P2P}(l,e)$ and $P^{LEM-P2P}(u,e)$ be the P2P traded amount of the seller $l \in L$ and the buyer $u \in U$ at time instant $e \in E$, where $P^{LEM-P2P}(l,e) \le P^{LEM-EX}(l,e), \forall l \in L$ and $P^{LEM-P2P}(u,e) \le P^{LEM-UN}(l,u), \forall u \in U$. As a seller can trade with multiple buyers via P2P and vice versa is true for the buyer, $P^{LEM-P2P}(l,e)$ and $P^{LEM-P2P}(u,e)$ can be expressed as:

$$P^{LEM-P2P}(l,e) = \sum\nolimits_{\mathrm{u}\in\mathrm{U}} P_u^{LEM-P2P}(l,e);\ \forall l \in L \subset T,\ \forall u \in U \subset T,\ \forall e \in E \tag{5}$$

$$P^{LEM-P2P}(u,e) = \sum\nolimits_{\mathrm{l}\in\mathrm{L}} P_l^{LEM-P2P}(u,e);\ \forall u \in U \subset T,\ \forall l \in L \subset T,\ \forall e \in E \tag{6}$$

Each seller $l \in L$ sells $P_u^{LEM-P2P}(l,e)$ to each buyer at a P2P selling price $n_u^{LEM-P2P}(l,e)$. Meanwhile each buyer $u \in U$ buys $P_l^{LEM-P2P}(u,e)$ from each seller at a P2P buying price $n_l^{LEM-P2P}(u,e)$ at a given time instant $e \in E$. $P^{LEM-GRD}(l,e) = (P^{LEM-EX}(l,e) - P^{LEM-P2P}(l,e)$ and $P^{LEM-GRD}(l,u) = \left(P^{LEM-UN}(l,u) - P^{LEM-P2P}(u,e)\right)$ are traded via the FiT rate $n^{FIT}(l,e)$ and ToU price $n^{TOU}(u,e)$, respectively. The earnings and expenses of each seller $l \in L$ and each buyer $u \in U$ in the LEM at a given time instant $e \in E$ are evaluated as follows:

$$D^{LEM}(l,e) = \left(\sum\nolimits_{u\in U} P_u^{LEM-P2P}(l,e) \times \Delta e \times n_u^{LEM-P2P}(l,e)\right) + \left(P^{LEM-GRD}(u,e) \times \Delta e \times n^{FIT}(l,e)\right);\ \forall l \in L \subset T,\ \forall u \in U \subset T,\ \forall e \in E \tag{7}$$

$$D^{LEM}(u,e) = \left(\sum_{l \in L} P^{LEM-P2P}(u,e)) \times \Delta\text{e} \times n_l^{LEM-P2P}(u,e)\right) + \left(P^{LEM-GRD}(u,e) \times \Delta e \times n^{TOU}(u,e)\right);\ \forall u \in U \subset T,\ \forall l \in L \subset T,\ \forall e \in E \tag{8}$$

where e indicates the instant length.

As for the BAU, there exists no trading with the BESSs of peers; hence $P^{P-DIS}(l,e) = 0$ and $P^{P-CHAR}(u,e) = 0$. Thus, (3) and (4) can be rewritten as:

$$P^{BAU-EX}(l,e) = \left(-P^{LOAD}(l,e) + P^{SOL}(l,e)\right) + \left(-P^{S-CHAR}(l,e)\right);\ \forall l \in L \subset T,\ \forall e \in E \tag{9}$$

$$P^{BAU-UN}(u,e) = \left(P^{LOAD}(u,e) - P^{SOL}(u,e)\right) + \left(-P^{S-DIS}(u,e)\right);\ \forall u \in U \subset T,\ \forall e \in E \tag{10}$$

For BAU, each seller $l \in L$ sells the entire $P^{BAU-EX}(l.e)$ at $n^{FIT}(l,e)$. Likewise, each buyer $u \in U$ buys the entire $P^{BAU-NU}(u,e)$ at $n^{TOU}(u,e)$. Therefore, the earning and expense of each seller $l \in L$ and each buyer $u \in U$ as per BAU at a given time instant $e \in E$ are computed as:

$$D^{BAU}(l,e) = P^{BAU-EX}(l,e) \times \Delta e \times n^{FIT}(l,e);\ \forall l \in L \subset T, \forall e \in E \tag{11}$$

$$D^{BAU}(u,e) = P^{BAU-UN}(u,e) \times \Delta e \times n^{TOU}(u,e);\ \forall u \in U \subset T, \forall e \in E \tag{12}$$

By subtracting (11) from (7), $\left(D^{LEM}(l,e) - D^{BAU}(l,e)\right)$ can be calculated. Similarly, $\left(D^{BAU}(u,e) - D^{LEM}(u,e)\right)$ can be calculated from the difference between (8) and (12).

3.4. Derivation of Constraints

3.4.1. Financial Constraints

The ToU price $n^{TOU}(u,e)$ consists of several components, such as the energy price $n^{EP}(u,e)$, EEG, tax and levy $n^{RT}(u,e)$ (where applicable), the energy supplier's margin $n^{ESM}(u,e)$, and the DSO/TSO's margin $n^{SOM}(u,e)$. In other words,

$$n^{TOU}(u,e) = n^{EP}(u,e) + n^{RT}(u,e) + n^{ESM}(u,e) + n^{SOM}(u,e);\ \forall u \in U \subset T, \forall e \in E \tag{13}$$

Let EEG, tax and levy, energy supplier's margin, and DSO/TSO's margin in the LEM be $n^{LEM-RT}(u,e)$, $n^{LEM-ESM}(u,e)$, and $n^{LEM-SOM}(u,e)$, respectively. In this study, while $n^{LEM-RT}(u,e)$ is equal to EEG, tax, and levy, $n^{RT}(u,e)$ $n^{LEM-ESM}(u,e)$ and $n^{LEM-SOM}(u,e)$ are not considered to be lower than $n^{ESM}(u,e)$ and $n^{SOM}(u,e)$, respectively, to avoid financial loss to energy suppliers and the DSO/TSO. These constraints are described in (14)–(16) as follows:

$$n^{LEM-RT}(u,e) = n^{RT}(u,e);\ \forall l \in L \subset T,\ \forall e \in E \tag{14}$$

$$n^{LEM-ESM}(u,e) \geq n^{ESM}(u,e);\ \forall l \in L \subset T, \forall e \in E \tag{15}$$

$$n^{LEM-SOM}(u,e) \geq n^{SOM}(u,e);\ \forall l \in L \subset T, \forall e \in E \tag{16}$$

Further, $n_l^{LEM-P2P}$ is required to be lower than $n^{ES}(u,e)$ to reduce the energy buying price, where $n^{LEM}(u,e)$ refers to the LEM transaction fee (platform cost). Additionally, the total buying price in the LEM, i.e., ($n_l^{LEM-P2P}(u,e) + n^{LEM}(u,e) + n^{LEM-RT}(u,e) + n^{LEM-ESM}(u,e) + n^{LEM-SOM}(u,e)$) , needs to be lower than $n^{TOU}(u,e)$ to benefit the buyers. As for the sellers' benefit, $n_u^{LEM-P2P}(l,e)$ is required to be higher than $n^{FIT}(l,e)$. These three constraints are illustrated in (17)–(19) as follows:

$$n_l^{LEM-P2P}(u,e) < n^{EP}(u,e);\ \forall u \in U \subset T,\ \forall e \in E \tag{17}$$

$$\left(n_l^{LEM-P2P}(u,e) + n^{LEM}(u,e) + n^{LEM-RT}(u,e) + n^{LEM-ESM}(u,e) + n^{LEM-SOM}(u,e)\right) < n^{TOU}(u,e);\ \forall u \in U \subset T,\ \forall e \in E \quad (18)$$

$$n_u^{LEM-P2P}(l,e) > n^{FIT}(l,e);\ \forall l \in L \subset T, \forall e \in E \quad (19)$$

Moreover, $\left(D^{LEM}(l,e) - D^{BAU}(l,e)\right)$ and $\left(D^{BAU}(u,e) - D^{LEM}(u,e)\right)$ should always be positive to guarantee benefit maximisation through the P2P trading-enabled *LEM*, such that:

$$\left(D^{LEM}(l,e) - D^{BAU}(l,e)\right) > 0;\ \forall l \in L \subset T, \forall e \in E \quad (20)$$

$$\left(D^{BAU}(u,e) - D^{LEM}(u,e)\right) > 0;\ \forall u \in U \subset T,\ \forall e \in E \quad (21)$$

3.4.2. System Power Balance

The *P2P* traded amounts need to abide by the local export and import limits prescribed by the DSO/TSO to ensure network integrity while LEM transactions are settled between sellers and buyers, such that:

$$0 \le P^{LEM-P2P}(l,e) \le P^{EXP}(l,e);\ \forall l \in L \subset T, \forall e \in E \quad (22)$$

$$0 \le P^{LEM-P2P}(u,e) \le P^{IMP}(u,e);\ \forall u \in U \subset T, \forall e \in E \quad (23)$$

where $P^{EXP}(l,e)$ and $P^{IMP}(u,e)$ denote export and import limits, respectively, at a given time instant $e \in E$.

The power sold by each seller $l \in L$ in the LEM $P^{LEM-EX}(l,e)$ is the summation of $P^{LEM-P2P}(l,e)$ and $P^{LEM-GRD}(l,e)$. In contrast, the total bought by each buyer $u \in U$ in $P^{LEM-UN}(u,e)$ is also the summation of $P^{LEM-P2P}(u,e)$ and $P^{LEM-GRD}(u,e)$. These are shown in (24) and (25), respectively.

$$P^{LEM-EX}(l,e) = P^{LEM-P2P}(l,e) + P^{LEM-GRD}(l,e);\ \forall l \in L \subset T, \forall e \in E \quad (24)$$

$$P^{LEM-UN}(u,e) = P^{LEM-P2P}(u,e) + P^{LEM-GRD}(u,e);\ \forall u \in U \subset T, \forall e \in E \quad (25)$$

In addition, the total sold P2P power $\sum_{l \in L} P^{LEM-P2P}(l,e)$ and the total P2P bought power $\sum_{u \in U} P^{LEM-P2P}(u,e)$ in the LEM should be equal, as captured in (26). In this case, $\left(\sum_{l \in L} P^{LEM-EX}(l,e) - \sum_{l \in L} P^{LEM-GRD}(l,e)\right) = \left(\sum_{u \in U} P^{LEM-UN}(u,e) - \sum_{u \in U} P^{LEM-GRD}(u,e)\right)$, as per (24) and (25). If $\sum_{l \in L} P^{LEM-EX}(l,e) = \sum_{u \in U} P^{LEM-UN}(u,e)$ at any time instant $\forall e \in E$, then $\sum_{l \in L} P^{LEM-GRD}(l,e) = \sum_{u \in U} P^{LEM-GRD}(u,e)$.

$$\sum_{l \in L} P^{LEM-P2P}(l,e) = \sum_{u \in U} P^{LEM-P2P}(u,e);\ \forall e \in E; \quad (26)$$

Furthermore, the overall upstream grid export and import through the *LEM* should also be lower than the *BAU* to help the DSO/TSO be relieved from the network congestion, as expressed in (27) and (28).

$$\sum_{l \in L} P^{LEM-GRD}(l,e) < \sum P^{BAU-EX}(l,e);\ \forall e \in E \quad (27)$$

$$\sum_{u \in U} P^{LEM-GRD}(u,e) < \sum P^{BAU-UN}(u,e);\ \forall e \in E \quad (28)$$

3.4.3. BESS Constraints

There are two types of BESS constraints: (1) self constraints and (2) peer constraints. Self constraints are satisfied to use BESSs for charging from one's own solar PV and discharging to meet one's own power demand. On the other hand, peer constraints are complied with to charge/discharge BESSs from/to the LEM. Equations (29)–(32) display the self constraints, where $SOC(t,e)$, c_t^{CHAR}, and c_t^{DIS} refer to the state-of-charge (SOC), charging efficiency, and discharging efficiency of LEM participant (either seller or buyer) $t \in T$ at a given time instant $e \in E$. $SOC(t,e)$ is bounded by the minimum and maximum SOCs symbolised by $SOC^{MIN}(t,e)$ and $SOC^{MAX}(t,e)$, respectively. At any time $e \in E$, the BESS charging energy $\left(P^{S-CHAR}(t,e) \times \Delta e\right)$ is limited by the minimum charging capacity $X^{MIN}(t,e)$ and maximum charging capacity $X^{MAX}(t,e)$, respectively. Similarly, the BESS discharging energy $\left(P^{S-DIS}(t,e) \times \Delta e\right)$ is also restricted by the minimum and maximum capacities, $Y^{MIN}(t,e)$ and $Y^{MAX}(t,e)$, respectively.

$$SOC(t,e) = SOC(t-1,e) + \left(c_t^{CHAR} \times P^{S-CHAR}(t,e) \times \Delta e\right) - \left(\frac{\left(P^{S-CHAR}(t,e) \times \Delta e\right)}{c_t^{DIS}}\right); \forall t \in T,\ \forall e \in E \quad (29)$$

$$SOC^{MIN}(t,e) \le SOC(t,e) \le SOC^{MAX}(t,e);\ \forall t \in T,\ \forall e \in E \quad (30)$$

$$X^{MIN}(t,e) \le \left(P^{S-CHAR}(t,e) \times \Delta e\right) \le X^{MAX}(t,e);\ \forall t \in T,\ \forall e \in E \quad (31)$$

$$Y^{MIN}(t,e) \le \left(P^{S-DIS}(t,e) \times \Delta e\right) \le Y^{MAX}(t,e);\ \forall t \in T,\ \forall e \in E \quad (32)$$

The BESS charging constraints through the P2P trading of each LEM participant $t \in T$ at a given time instant $e \in E$ are given in (33)–(35). The peer charging order $\left(P^{P-CHAR}(t,e) \times \Delta e\right)$ is bounded by the rate of peer charging $X^{P-CHAR-RT}(t,e)$ and available capacity to charge the BESS $\left(P^{P-CHAR-AV}(t,e) \times \Delta e\right)$, where $\left(P^{SOL-PK}(l) \times \Delta e\right)$ refers to the peak solar PV of each LEM participant $t \in T$. Similarly, (36)–(38) demonstrate the BESS discharging constraints through the *P2P* trading of each LEM participant $t \in T$ at a given time instant $e \in E$, which reveal that the peer discharging order $\left(P^{P-DIS}(t,e) \times \Delta e\right)$ is restricted by the rate of peer discharging $Y^{P-DIS-RT}(t,e)$ and the stored energy in the BESS to discharge $\left(P^{P-DIS-AV}(t,e) \times \Delta e\right)$, where $\left(P^{LOAD-PK}(l) \times \Delta e\right)$ represents the peak load power of each LEM participant $t \in T$.

$$\left(P^{P-CHAR}(t,e) \times \Delta e\right) = min\left\{X^{P-CHAR-RT}(t,e),\ P^{P-CHAR-AV}(t,e) \times \Delta e\right\}; \forall t \in T, \forall e \in E \quad (33)$$

$$X^{P-CHAR-RT}(t,e) = \left(X^{MAX}(t,e) \times c_t^{CHAR}\right) - \left(P^{S-CHAR}(t,e) \times \Delta e\right);\ \forall t \in T,\ \forall e \in E \quad (34)$$

$$P^{P-CHAR-AV}(t,e) \times \Delta e = SOC^{MAX}(t,e) - SOC(t-1,e) - \left(P^{SOL-PK}(l) \times \Delta e\right) - (P^{S-CHAR}(t,e) \times \Delta e;\ \forall t \in T,\ \forall e \in E \quad (35)$$

$$P^{P-DIS}(t,e) \times \Delta e = min\left\{Y^{P-DIS-RT}(t,e),\ P^{P-DIS-AV}(t,e) \times \Delta e\right\};\ \forall t \in T,\ \forall e \in E \quad (36)$$

$$Y^{P-DIS-RT}(t,e) = \left(Y^{MAX}(t,e) \times c_t^{DIS}\right) - \left(P^{S-DIS}(t,e) \times \Delta e\right); \forall t \in T,\ \forall e \in E \quad (37)$$

$$P^{P-DIS-AV}(t,e) \times \Delta e = SOC(t-1,e) - SOC^{MIN}(t,e) - \left(P^{LOAD-PK}(l) \times \Delta e\right) - (P^{S-DIS}(t,e) \times \Delta e;\ \forall t \in T,\ \forall e \in E \quad (38)$$

4. Case Study and Results

In this section, the formulated P2P trading-driven LEM mechanism is applied in the context of Berlin, Germany, by means of a case study that contains existing consumers, prosumers, energy suppliers, and the network operator. The P2P trading time instant is set to an interval of 15 min (i.e., $\Delta e = 15$). REMIX IDE was adopted to write smart contracts and it was tested on the Ethereum blockchain development tool Ganache CLI v6.12.2. The web3.py library was also used to connect UI to the smart contract and the blockchain database. This section also presents the comparison between the BAU (Case A) and the proposed LEM (Case B) to highlight the superior performance of the P2P trading.

4.1. Participants Bidding

Figure 6 illustrates the bidding rate for 10 randomly selected prosumers and 10 consumers (i.e., $|L|$ = 10, $|U|$ = 10), who are customers of two different energy suppliers at a given P2P trading instant $e \in E$. Prosumers place bids to sell at a price greater than the FiT rate $n^{FIT}(l,e)$, but lower than the energy portion of grid *ToU* buy price $n^{EP}(u,e)$. The prices for prosumers in Euro/kWh are shown in Figure 6a. On the other hand, consumers pay extra fees (as demonstrated in Table 1) on top of the energy fee while engaging in P2P trading in LEM, but it is lower than the respective grid *ToU* buy price $n^{TOU}(u,e)$. Figure 6b presents the prices for consumers in Euro/kWh.

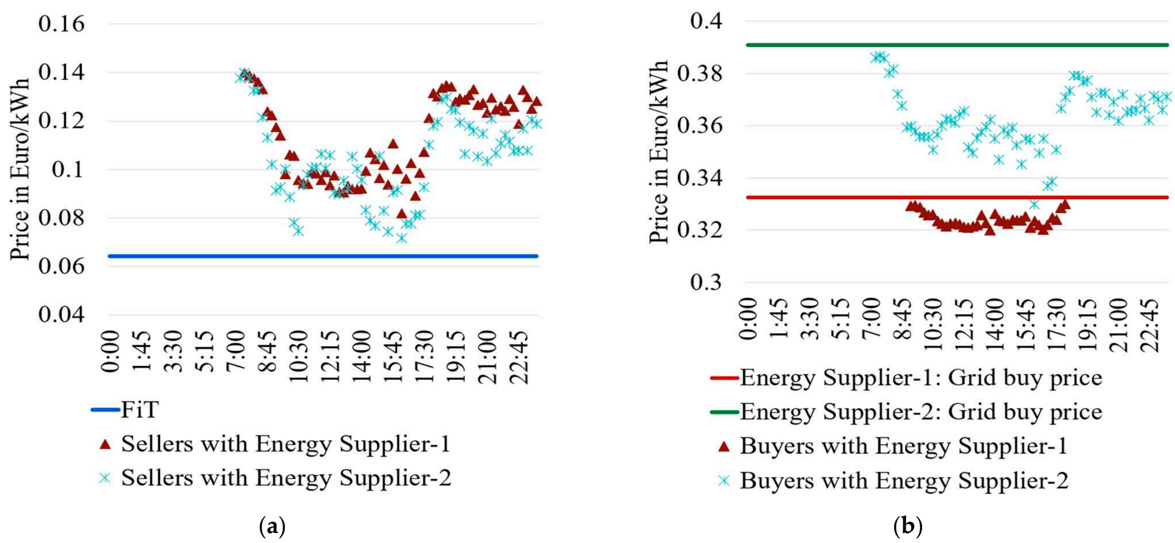

Figure 6. Energy bid rates for 10 randomly chosen prosumers and 10 consumers at a given time instant (**a**) sellers bid rates, and (**b**) buyers bid rates.

4.2. Reduction in Grid Import/Export and Comparision with [44]

Figure 7 presents the selling and buying profiles of the considered network in BAU (Case A) and LEM (Case B). The peak power sold/bought to the power grid in the afternoon/evening was decreased in LEM by 61.52%/26.93%, which was a remarkable figure, due to P2P contracts in the LEM. Through P2P contracts, BESSs were charged to store energy at lower prices and discharged in lieu of higher prices for substantial monetary gains. This resulted in a 61.52%/26.93% reduction in export/import to/from the power grid.

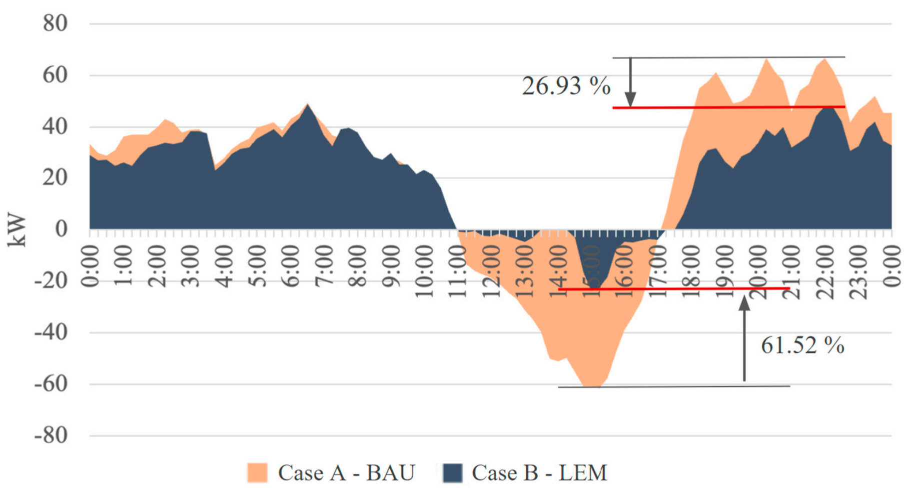

Figure 7. Trading with the power grid (selling and buying amounts in kW are represented by negative and positive signs, respectively).

Figure 8 compares the grid import/export results of the proposed model and [44], and shows that the proposed model reduced grid imports by 13.02% more than [44] during the afternoon period, which significantly mitigated the impact of high solar PV penetration on the grid. Moreover, while the proposed model's export reduction was lower than [44], it still supported the grid by reducing its export by 26.93%, thus controlling grid expenditures and flexibility requirements.

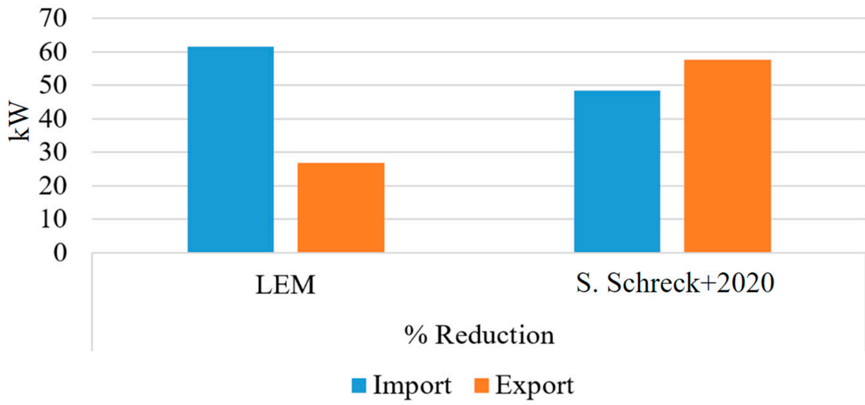

Figure 8. Comparison between import and export of proposed LEM and the study of S. Screck+2020 [44].

4.3. Participants' Daily Electricity Cost Reduction and Comparison with [44]

Figure 9 reveals the average daily electricity cost to consumers, prosumers with solar PV systems, and prosumers with solar PV systems and BESSs for BAU and the LEM. As can be observed from Figure 8, on average, consumers, prosumers with solar PV systems, and prosumers with solar PV systems and BESSs would pay 5.8 Euro, 2.1 Euro, and 1 Euro, respectively, if P2P trading was performed in the LEM. Strikingly, these costs are 0.2 Euro, 0.3 Euro, and 0.4 Euro lower than those of BAU, confirming the electricity cost reduction of all types of LEM participants.

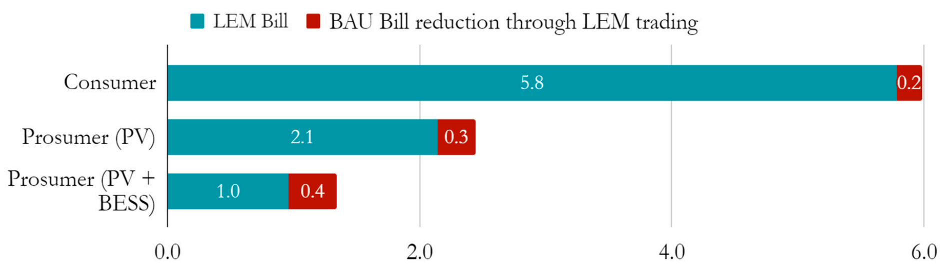

Figure 9. Daily electricity bill comparison (BAU vs. LEM).

The percentage daily cost reduction of the LEM participants is shown in Table 2, in which consumers, prosumers with solar PV systems, and prosumers with solar PV systems and BESSs can minimise their energy costs by 4.9%, 15.7%, and 29.8%, respectively, on average over the course of 24 h. Thus, the more customers invest in renewables, the more financial returns they attain, although no investment still benefits them, to some extent. Furthermore, compared with [44], the proposed model resulted in an average reduction of 16.5% in electricity costs, and all types of participants would stand to gain additional profits.

Table 2. An example of the comparative rates between BAU and P2P.

	Consumer	Prosumer (PV)	Prosumer (PV + BESS)
BAU vs. LEM	4.9%	15.7%	29.8%

4.4. Energy Suppliers' Improved Daily Margins

The formulated P2P trading-based LEM structure kept the margins of the energy suppliers above the BAU levels; the comparisons are depicted in Figure 10. This was because energy suppliers would retain their portions every time P2P transactions were conducted in the LEM. BESS charging and discharging through peers actually enhanced energy trading volumes, resulting in increased margins for both energy suppliers. In this case study, the margins of Energy Supplier-1 and Energy Supplier-2 were improved by 7.4% and 4.5%, respectively. Energy Supplier-1 was the winner, as it had 66.67% more BESS customers compared with Energy Supplier-2. Hence, the inclusion of BESS in the LEM improved energy suppliers' margins.

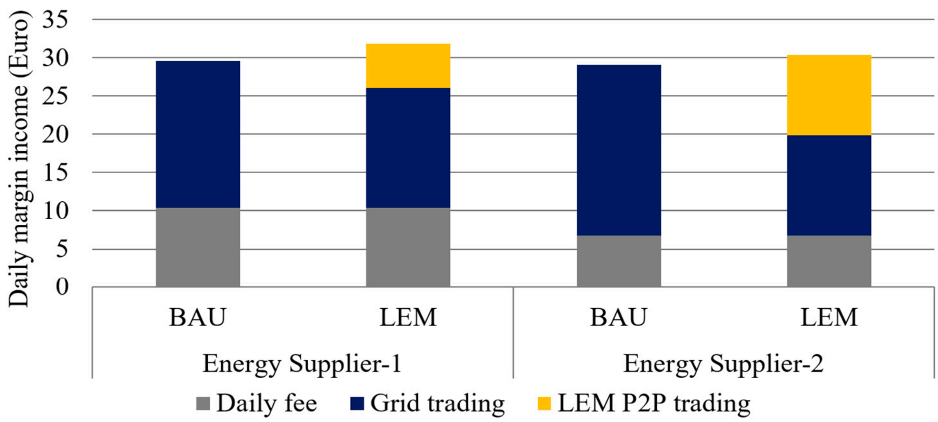

Figure 10. Daily income margin of energy suppliers.

4.5. DSO/TSO's Increased Daily Income

The DSO/TSO's daily incomes as per BAU and LEM are presented in Figure 11, which indicates that the DSO/TSO would receive an additional income of 11 Euro (5.4% more than usual BAU) through the P2P trading in the LEM. This was caused by an increase in the energy trading volumes by the peer-facilitated BESS charging and discharging. Although the daily income of DSO/TSO apparently did not grow much with the introduction of the LEM, the DSO/TSO could veritably reduce its budget allocated to power grid operation and maintenance due to the lower export/import to/from the power grid and attain long-term benefits.

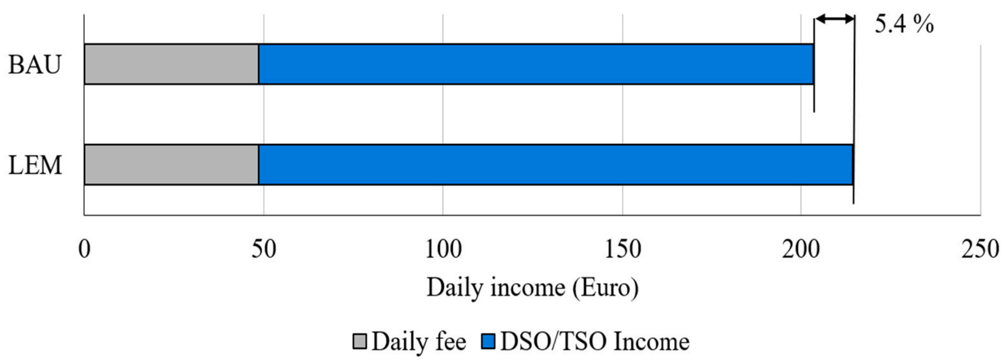

Figure 11. Daily income margin of DSO/TSO.

4.6. Cost Comparison of Ethereum vs. Polygon Blockchain

The costs associated with the execution of different functions of the smart contracts in Ethereum and polygon blockchains are demonstrated in Table 3. The cost of operating a P2P trading-driven LEM on the Ethereum blockchain platform was found to be significantly higher (around 100% higher) than that of the Polygon blockchain. This was due to the fact that the transaction speed of the Ethereum network was much lower (approximately 15–17 transactions per second) compared with the Polygon network (approximately 65,000 transactions per second). Owing to Ethereum's low transaction speed, the network congestion was also high, resulting in higher gas fees. Therefore, Polygon blockchain is identified as the most suitable platform to accommodate the proposed LEM trading.

Table 3. Transaction cost for executing the smart contract in the LEM.

SI#	Action	Paid by	Gas	Cost of Using Blockchain (Euro)	
				Ethereum	Polygon
1	Smart Contract Deployment	Admin	3928062	89.55	0.72
2	User Register	Users	43967	1.00	0.01
3	Bidding	Participants	113234	2.58	0.02
4	Calculation	Admin	362957	8.27	0.07
5	Billing	Admin	101403	2.31	0.02
6	Settlement	Admin	59259	1.35	0.01

5. Conclusions

In this paper, a P2P trading-driven LEM mechanism was proposed, and the financial viability of such a LEM was also analysed. To do so, a blockchain-based platform was designed for the LEM, in which various end-users, including consumers, prosumers with solar PVs, and prosumers with solar PVs and BESSs, were facilitated to carry out frequent P2P energy trading among one another following several technical and operational constraints of the LEM that included the system power balance, price constraints, and BESS functional constraints, guaranteeing the financial interests of the participants and other stakeholders, such as energy suppliers and the DSO/TSO. The formulated LEM smart contract was tested on both Ethereum and Polygon blockchains to determine the most affordable one. Moreover, the overall blockchain-empowered LEM strategy was validated by performing a German case study where real-world data profiles of several participants, two energy suppliers, and the DSO/TSO were used. The extensive simulation results were also compared with the BAU, and the comparative results emphasised the domineering performance of the proposed LEM trading model.

However, the complexity of current legal and regulatory frameworks, the complexity of the choice of the correct blockchain, and the understanding of and buying by the common public present obstacles to the swift adoption of these systems. To pave the way for decentralised solutions, there is a need to reassess the relevance and necessity of these regulations and identify and compare the available chains. A potential future study will be to implement the LEM framework in the Solana blockchain, which is adopted by companies, such as Powerledger. Decentralised energy systems and the use of tokenisation in these systems using blockchain have the potential to create more efficient and resilient energy markets. Additional future work will also include the elaboration of legal and regulatory frameworks around the decentralisation and tokenisation of energy.

Author Contributions: L.A.: Conceptualisation, Formal analysis, Investigation, Methodology, Validation, Writing—original draft, Writing—review and editing, and Final approval. M.I.A.: Conceptualisation, Methodology, Visualisation, Visualisation, Writing—review and editing, and Final approval. N.B.O.: Conceptualisation, Data curation, Formal analysis, Visualisation, Writing—review and editing, and Final approval. J.P.: Conceptualisation, Data curation, Formal analysis, Visualisation, Writing—review and editing, and Final approval. V.B.: Conceptualisation, Validation, Visualisation, Supervision, Writing—review and editing, and Final approval. A.M.: Conceptualisation, Validation, Visualisation, Supervision, Writing—review and editing, and Final approval. V.T.: Conceptualisation, Visualisation, Supervision, Writing—review and editing, and Final approval. J.G.: Conceptualisation, Visualisation, Supervision, Writing—review and editing, and Final approval. S.M.M.: Conceptualisation, Visualisation, Supervision, Writing—review and editing, and Final approval. All authors have read and agreed to the published version of the manuscript.

Funding: Open Access funding provided by the Qatar National Library.

Data Availability Statement: Not applicable.

Acknowledgments: Authors would like to express special thanks to the Powerledger product team and management for their advice, suggestions, and guidelines during this research.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Davoudi, M.; Moeini-Aghtaie, M. Local energy markets design for integrated distribution energy systems based on the concept of transactive peer-to-peer market. *IET Gener. Transm. Distrib.* **2021**, *16*, 41–56.
2. Canizes, B.; Soares, J.; Almeida, J.; Vale, Z. Hour-ahead energy resource scheduling optimization for smart power distribution networks considering local energy market. *Energy Rep.* **2022**, *8*, 575–582.
3. Ali, L.; Azim, M.I.; Peters, J.; Bhandari, V.; Menon, A.; Tiwari, V.; Green, J.; Muyeen, S. Blockchain-based local energy market enabling P2P trading: An Australian collated case study on energy users, retailers and utilities. *IEEE Access* **2022**, *10*, 124429–124447.
4. Azim, M.I.; Tushar, W.; Saha, T.K. Coalition graph game-based P2P energy trading with local voltage management. *IEEE Trans. Smart Grid* **2021**, *12*, 4389–4402.
5. Strepparava, D.; Nespoli, L.; Kapassa, E.; Touloupou, M.; Katelaris, L.; Medici, V. Deployment and analysis of a blockchain-based local energy market. *Energy Rep.* **2021**, *8*, 99–113.
6. Reihani, E.; Siano, P.; Genova, M. A new method for peer-to-peer energy exchange in distribution grids. *Energies* **2020**, *13*, 799.
7. Ali, L. Development and Improvement of Renewable Energy Integrated with Energy Trading Schemes Based on Advanced Optimization Approaches. Ph.D. Thesis, School of Electrical Engineering, Computing and Mathematical Sciences, Curtin University, Perth, Australia, 2021. Available online: http://hdl.handle.net/20.500.11937/84949 (accessed on 29 April 2023).
8. Ali, L.; Azim, M.I.; Peters, J.; Pashajavid, E.; Bhandari, V.; Menon, A.; Green, J. Local Energy Markets Improve Investment Returns of Residential BESS by Arbitrage Opportunities. In Proceedings of the 2022 IEEE Sustainable Power and Energy Conference (iSPEC), Perth, Australia, 4–7 December 2022; pp. 1–5. [CrossRef]
9. Soto, E.A.; Bosman, L.B.; Wollega, E.; Leon-Salas, W.D. Peer-to-peer energy trading: A review of the literature. *Appl. Energy* **2021**, *283*, 116268.
10. Capper, T.; Gorbatcheva, A.; Mustafa, M.A.; Bahloul, M.; Schwidtal, J.M.; Chitchyan, R.; Andoni, M.; Robu, V.; Montakhabi, M.; Scott, I.J.; et al. Peer-to-peer, community self-consumption, and transactive energy: A systematic literature review of local energy market models. *Renew. Sustain. Energy Rev.* **2022**, *162*, 112403.
11. Ali, L.; Azim, M.I.; Peters, J.; Bhandari, V.; Menon, A.; Tiwari, V.; Green, J. A local energy market benefiting power grids and energy users: A P2P trading-based case study. In Proceedings of the International Conference on Smart Grid, Istanbul, Turkey, 27–29 June 2022; pp. 90–95.
12. Ali, L.; Azim, M.I.; Peters, J.; Bhandari, V.; Menon, A.; Tiwari, V.; Green, J. A win-win local energy market for participants, retailers, and the network operator: A peer-to-peer trading-driven case study. In Proceedings of the International Conference on Industrial Informatics, Perth, Australia, 25–28 July 2022; pp. 175–179.
13. Heren, L.; Ilak, P.; Raj, I. Effects of local electricity trading on power flows and voltage levels for different elasticities and prices. *Energies* **2019**, *12*, 4708.
14. Karami, M.; Madlener, R. Business models for peer-to-peer energy trading in Germany based on households' beliefs and preferences. *Appl. Energy* **2022**, *306*, 118053.
15. Georgarakis, E.; Bauwens, T.; Pronk, A.-M.; AlSkaif, T. Keep it green, simple and socially fair: A choice experiment on prosumers' preferences for peer-to-peer electricity trading in the Netherlands. *Energy Policy* **2021**, *159*, 112615.
16. Dong, J.; Song, C.; Liu, S.; Yin, H.; Zheng, H.; Li, Y. Decentralized peer-to-peer energy trading strategy in energy blockchain environment: A game-theoretic approach. *Appl. Energy* **2022**, *325*, 119852.
17. Hahnel, U.J.; Herberz, M.; Pena-Bello, A.; Parra, D.; Brosch, T. Becoming prosumer: Revealing trading preferences and decision-making strategies in peer-to-peer energy communities. *Energy Policy* **2019**, *137*, 111098.
18. Hahnel, U.J.; Fell, M.J. Pricing decisions in peer-to-peer and prosumer-centred electricity markets: Experimental analysis in Germany and the United Kingdom. *Renew. Sustain. Energy Rev.* **2022**, *162*, 112419.
19. Kirchhoff, H.; Strunz, K. Key drivers for successful development of peer-to-peer microgrids for swarm electrification. *Appl. Energy* **2019**, *244*, 46–62.
20. An, J.; Hong, T.; Lee, M. Determining the optimal trading price of electricity for energy consumers and prosumers. *Renew. Sustain. Energy Rev.* **2022**, *154*, 111851.
21. Ali, L.; Peters, J.; Azim, M.I.; Pashajavid, E.; Bhandari, V.; Menon, A.; Green, J. How P2P Trading Helps an Electricity Retailer Exposed to Volatile Spot Prices: A Case Study. In Proceedings of the 2022 IEEE Sustainable Power and Energy Conference (iSPEC), Perth, Australia, 4–7 December 2022; pp. 1–5. [CrossRef]
22. Wang, J.; Zhang, J.; Li, L.; Lin, Y. Peer-to-peer energy trading for residential prosumers with photovoltaic and battery storage systems. *IEEE Syst. J.* **2022**, *17*, 151–163. [CrossRef]

23. Ali, L.; Muyeen, S.M.; Bizhani, H. Optimal Sizing and Profit Maximization of Clustered Microgrid using Game Theory Techniques. In Proceedings of the 2019 9th International Conference on Power and Energy Systems (ICPES), Perth, Australia, 10–12 December 2019; pp. 1–6. [CrossRef]
24. Chau, S.C.-K.; Xu, J.; Bow, W.; Elbassioni, K. Peer-to-peer energy sharing: Effective cost-sharing mechanisms and social efficiency. In Proceedings of the International Conference on Future Energy Systems, New York, NY, USA, 25–28 June 2019; pp. 215–225.
25. Ali, L.; Muyeen, S.M.; Bizhani, H.; Ghosh, A. Comparative study on game-theoretic optimum sizing and economical analysis of a networked microgrid. *Energies* **2019**, *12*, 4004.
26. Ali, L.; Azim, M.I.; Peters, J.; Bhandari, V.; Menon, A.; Tiwari, V.; Muyeen, S.M. Application of a Community Battery-Integrated Microgrid in a Blockchain-Based Local Energy Market Accommodating P2P Trading. *IEEE Access* **2023**, *11*, 29635–29649. [CrossRef]
27. Li, L.; Zhang, S. Peer-to-peer multi-energy sharing for home microgrids: An integration of data-driven and model-driven approaches. *Int. J. Electr. Power Energy Syst.* **2021**, *133*, 107243.
28. Paudel, A.; Chaudhari, K.; Long, C.; Gooi, H.B. Peer-to-peer energy trading in a prosumer-based community microgrid: A game-theoretic model. *IEEE Trans. Ind. Electron.* **2019**, *66*, 6087–6097.
29. Xia, Y.; Xu, Q.; Qian, H.; Cai, L. Peer-to-peer energy trading considering the output uncertainty of distributed energy resources. *Energy Rep* **2022**, *8*, 567–574.
30. Fu, M.; Xu, Z.; Wang, N.; Lyu, X.; Xu, W. Peer-to-peer plus electricity transaction within community of active energy agents regarding distribution network constraints. *Energies* **2020**, *13*, 2408.
31. Zhang, J.; Hu, C.; Zheng, C.; Rui, T.; Shen, W.; Wang, B. Distributed peer-to-peer electricity trading considering network loss in a distribution system. *Energies* **2019**, *12*, 4318.
32. Botelhoad, D.; de Oliveiraad, L.; Diasad, B.; Soaresbd, T.; Morae-sac, C. Integrated prosumers–DSO approach applied in peer-to-peer energy and reserve tradings considering network constraints. *Appl. Energy* **2022**, *317*, 119125.
33. Jin, Y.; Choi, J.; Won, D. Pricing and operation strategy for peer-to-peer energy trading sing distribution system usage charge and game theoretic model. *IEEE Access* **2020**, *8*, 137720–137730.
34. Mehdinejad, M.; Shayanfar, H.; Mohammadi-Ivatloo, B. Peer-to-peer decentralized energy trading framework for retailers and prosumers. *Appl. Energy* **2022**, *308*, 118310.
35. Xiao, Y.; Wang, X.; Pinson, P.; Wang, X. Transactive energy based aggregation of prosumers as a retailer. *IEEE Trans. Smart Grid* **2020**, *11*, 3302–3312.
36. Ali, L. Optimisation of energy storages in microgrid for power generation uncertainties. Master's Thesis, School of Electrical and Computer Engineering, Curtin University, Perth, Australia, 2016. Available online: http://hdl.handle.net/20.500.11937/48485 (accessed on 29 April 2023).
37. Ali, L.; Azim, M.I.; Bhandari, V.; Menon, A.; Tiwari, V.; Green, J.; Bizhani, H.; Muyeen, S. P2P as a smarter way of energy trading: A game theoretic case study for multi-microgrids. In Proceedings of the International Conference on Smart Grid, Istanbul, Turkey, 27–29 June 2022; pp. 285–289.
38. Angaphiwatchawal, P.; Sompoh, C.; Chaitusaney, S. A multi-k double auction pricing mechanism for peer-to-peer energy trading market of prosumers. In Proceedings of the International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology, Chiang Mai, Thailand, 19–22 May 2021; pp. 1–4.
39. Xu, S.; Zhao, Y.; Li, Y.; Zhou, Y. An iterative uniform-price auction mechanism for peer-to-peer energy trading in a community microgrid. *Appl. Energy* **2021**, *298*, 117088.
40. Lyu, C.; Jia, Y.; Xu, Z. Fully decentralized peer-to-peer energy sharing framework for smart buildings with local battery system and aggregated electric vehicles. *Appl. Energy* **2021**, *299*, 117243.
41. Schreck, S.; Thiem, S.; Amthor, A.; Metzger, M.; Niessen, S. Activating current and future flexibility potential in the distribution grid through local energy markets. In Proceedings of the CIRED Berlin Workshop, Berlin, Germany, 22–23 September 2020; pp. 606–609.
42. Luth, A.; Zepter, J.M.; del Granado, P.C.; Egging, R. Local electricity market designs for peer-to-peer trading: The role of battery flexibility. *Appl. Energy* **2018**, *229*, 1233–1243. [CrossRef]
43. Anees, A.; Dillon, T.; Chen, Y.-P.P. A novel decision strategy for a bilateral energy contract. *Appl. Energy* **2019**, *253*, 113571. [CrossRef]
44. Schreck, S.; Thiem, S.; Amthor, A.; Metzger, M.; Niessen, S. Analyzing potential schemes for regulated electricity price components in local energy markets. In Proceedings of the International Conference on the European Energy Market, Stockholm, Sweden, 16–18 September 2020; pp. 1–6.
45. Nguyen, S.; Peng, W.; Sokolowski, P.; Alahakoon, D.; Yu, X. Optimizing rooftop photovoltaic distributed generation with battery storage for peer-to-peer energy trading. *Appl. Energy* **2018**, *228*, 2567–2580. [CrossRef]
46. Morstyn, T.; Teytelboym, A.; Hepburn, C.; McCulloch, M.D. Integrating P2P energy trading with probabilistic distribution locational marginal pricing. *IEEE Trans. Smart Grid* **2020**, *11*, 3095–3106. [CrossRef]
47. Rashidizadeh-Kermani, H.; Vahedipour-Dahraie, M.; Shafie-khah, M.; Siano, P. Optimal bidding of profit-seeking virtual associations of smart prosumers considering peer to peer energy sharing strategy. *Int. J. Electr. Power Energy Syst.* **2021**, *132*, 107175. [CrossRef]

48. Chung, K.-H.; Hur, D. Towards the design of P2P energy trading scheme based on optimal energy scheduling for prosumers. *Energies* **2020**, *13*, 5177. [CrossRef]
49. Guerrero, J.; Chapman, A.C.; Verbi, G. Local energy markets in LV networks: Community based and decentralized P2P approaches. In Proceedings of the PowerTech, Milan, Italy, 23–27 June 2019; pp. 1–7.
50. Ali, L.; Bhandari, V.; Peters, J.; Tushar, W.; Nizami, S.; Menon, A.; Tiwari, V.; Green, J.; Saha, T. Discover How You Can Save Money and Help the Environment with Local Energy Markets: An Australian Case Study! Smart Energy Council, Industry Updates, Press Releases, Australia. 27 March 2023. Available online: https://smartenergy.org.au/articles/discover-how-you-can-save-money-and-help-the-environment-with-local-energy-markets-an-australian-case-study/ (accessed on 29 April 2023).
51. Elkazaz, M.; Sumner, M.; Thomas, D. A hierarchical and decentralized energy management system for peer-to-peer energy trading. *Appl. Energy* **2021**, *291*, 116766. [CrossRef]
52. Faia, R.; Soares, J.; Pinto, T.; Lezama, F.; Vale, Z.; Corchado, J.M. Optimal model for local energy community scheduling considering peer to peer electricity transactions. *IEEE Access* **2022**, *9*, 12420–12430. [CrossRef]
53. Electrical Load Profiles for Residential Buildings in Germany. Available online: https://solar.htw-berlin.de/elektrische-lastprofile-fuer-wohngebaeude/ (accessed on 29 December 2022).
54. Vattenfall. Convenient Energy Supply with Heat Contracting. Available online: https://xn{-}{-}wrme-loa.vattenfall.de/fachgebiet/contracting/?utm_term=vattenfall%20energy&utm_medium=ppc&utm_campaign=&utm_source=adwords&hsa_kw=vattenfall%20energy&hsa_tgt=kwd-383983153100&hsa_ver=3&hsa_grp=119774638955&hsa_cam=12501423528&hsa_src=g&hsa_mt=e&hsa_acc=4791536886&hsa_net=adwords&hsa_ad=619045377827&gclid=CjwKCAiA76-dBhByEiwAA0_s9b36jm85hi1TvvpvTNev-r6-AfGE3_agD4qCvCZv8oEXl2WW85ktNBoCMTwQAvD_BwE (accessed on 29 December 2022).
55. E.ON. The E.ON Group: A Unique Company. Available online: https://www.eon.com/en/about-us.html (accessed on 29 December 2022).
56. Stromnetz Berlin. Power for You and Berlin at Every Time. Available online: https://www.stromnetz.berlin/en/ (accessed on 29 December 2022).
57. Vattenfall. Electricity for Berlin. Available online: https://www.vattenfall.de/stromtarife?plz=13125&consumption=3000&place=Berlin&energyTypeSelected=electricity#products (accessed on 29 December 2022).
58. E.ON's Cheapest Online Rates. Available online: https://www.eon.de/de/pk/strom/stromanbieter/guenstiger-stromanbieter.html?utm_source=google&utm_medium=cpc&keyword=eon%20de%20tarife&mc=0512212000&gclid=CjwKCAjw7cGUBhA9EiwArBAvos1sIWEJR2FfzzjN8dmp3k1uEF_9S6PfEKJrPTBWvcv7-aJcGuwJ3hoCotsQAvD_BwE&gclsrc=aw.ds (accessed on 29 December 2022).
59. Feed-in Tariff from 30 July 2022. Available online: https://www.solaranlagen-portal.com/photovoltaik/wirtschaftlichkeit/einspeiseverguetung#:~:text=Einspeiseverg%C3%BCtung%20ab%20dem%2030.%20Juli,Anlagen%20kleiner%20als%2040%20kWp (accessed on 29 December 2022).
60. Preisblatt der Stromnetz Berlin GmbH. Available online: https://www.stromnetz.berlin/files/globalassets/dokumente/entgelte/zugang/entgelte-01.01.2021/nne-b-2021.pdf (accessed on 29 December 2022).
61. EEG Financing. Available online: https://www.netztransparenz.de/EEG/EEG-Umlagen-Uebersicht (accessed on 29 December 2022).
62. Today's Cryptocurrency Prices by Market Cap. Available online: https://coinmarketcap.com/ (accessed on 29 December 2022).
63. Wongthongtham, P.; Marrable, D.; Abu-Salih, B.; Liu, X.; Morrison, G. Blockchain-enabled Peer-to-Peer energy trading. *Comput. Electr. Eng.* **2021**, *94*, 107299. [CrossRef]