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Energy Policy Instruments for Distributed Ledger Technology Empowered Peer-to-Peer Local Energy Markets

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ABSTRACT Peer-to-peer energy trading and next generation local energy market mechanisms are expected to provide new use cases and opportunities within the future sharing economy landscape. To this anticipation, we propose alternative incentive mechanisms as energy policy instruments that can be used by policy makers for directly supporting local energy producers, and hence indirectly the consumers, at current local energy markets using capabilities provided by contemporary distributed ledger technology. Under such peer-to-peer local market setting, we first detail market pricing and relevant market parameters thoroughly, and then we discuss fair incentive distribution to local producers in detail, by means of two distinct incentive systems what we call as the fixed stipend and the decaying stipend incentive mechanisms, respectively. We provide an analysis of market pricing and market parameters under German power market conditions, and an illustration of proposed support instruments with resorting to three scenarios experimented on a local energy market test bed that is equipped with realistic energy generation and consumption profiles for its participants.

INDEX TERMS Blockchain technology, distributed ledger technology, energy policy, fair incentive mechanisms, local energy markets, local market pricing, peer-to-peer energy trading, sharing economy.

I. INTRODUCTION

Stages of the industrial era is evolved alongside energy technologies. The first industrial revolution started with the invention of the steam engines and advanced through corresponding infrastructure supported by derivatives such as the factories and railways. Electrification, invention of combustion engines and evolving mass production were the major drivers of the second industrial era. The main pillars of the third industrial era were internet technologies, advance molecular biology, industrial internet of things, and renewable and distributed energy technologies. Transition to decentralized/green energy resources and digital transformation of the existing industrial infrastructure had been the biggest achievements of this epoch. Rifkin [1] summarized the third industrial revolution as ‘‘a new convergence of communication and energy’’ to design and operate a powerful modern energy infrastructure. While the industry is evolving towards the next stage, the fourth industrial revolution is launched. The fourth industrial era, in other terms *Industry 4.0*, leads to the fusion of cutting-edge technologies in the physical, cyber and biological landscapes to develop new forms of *cyber-physical-systems* (CPS). Transactive Energy Systems are being designed by taking the advantage of advanced control, economic and operational functionalities to dynamically balance the electrical demand and supply within the electrical grid using advanced *information and communication technologies* (ICT). The main drivers of the fifth industrial era are expected to be artificial intelligence, autonomous robotics, advanced biotechnology, cognitive computing, additive manufacturing, fully-autonomous vehicles, and in particular, next generation *distributed ledger technology* (DLT).

Energy systems are multi-layer complex CPS composed of the physical, communication, control, power markets, business, and energy politics layers as illustrated in Fig. 1. Physical layer accommodates the entire supply chain of energy systems starting from large scale energy generators to the final energy consumers, and soon to be introduced in the next section, the prosumers. The system consists of power transmission and distribution grids as well as relevant or

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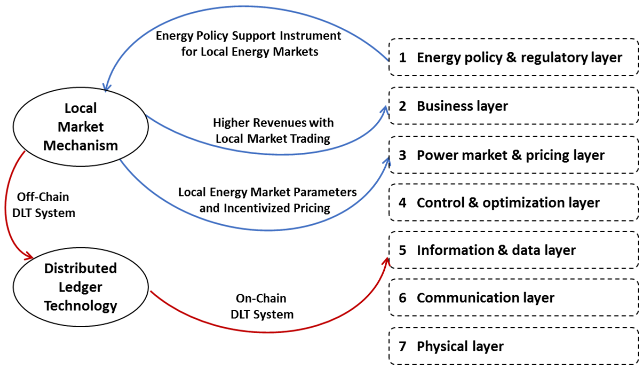

FIGURE 1. Energy system as a multi-layer CPS.

corresponding infrastructure of ICT such as phasor measurement units devices and electric meters. Communication layer is responsible to enable all types of communication technologies such as fiber-optic Wi-Fi and other emerging technologies. All type of information and data-related activities are handled under the information layer. Reliability, cyber-security, robustness, scalability, power consumption characteristics, economic viability of the communication technologies; and, effectiveness and interoperability of used protocols are critical factors that should be considered while designing modern, efficient, and smart power systems [2]. Information and data layer is located between the control and communication layers, and devolving on all types of data processing, analysis and cyber-security functionalities.

DLT-related applications are utilized under this layer. DLT allows to diversify next generation energy policy instruments which may accommodate even very complex mechanisms and track recording. DLT applications can be categorized in terms of architectural design in three domains: on-chain, off-chain, and side-chain. Everything related to transactions and other core functionalities of DLT is carried out in *on-chain* domain. *Off-chain* domain accommodates various supplementary features and implementations which can be linked to the on-chain domain. Additional off-chain features can be listed as business logic applications, additional data storage repositories, artificial intelligence based algorithms and optimization applications. Off-chain domain can be used to connect cyber and physical worlds and solves many scalability and interoperability issues of pure on-chain DLT applications. *Side-chain* allows DLT network to be coupled to other on-chain domains and also used for separation of DLT domains. Side-chain networks run in parallel to the on-chain networks [3]. Advanced control and optimization tools utilized to control the operation of smart energy systems that include decision-making and optimization algorithms, are deployed in this layer.

Power market and pricing layer is responsible for managing the track recording of power flow and monetary transactions simultaneously between the buyer and sellers. Power market regulations in competitive and structured markets determines the rules and roles within the marketplace. Wholesale and local market trading operations can vary depending on the location of the market. Business domain players such as energy investors, trading companies, transmission and distribution system operators are conventional stakeholders of today's power markets. Liberalization stages of the power market led diversification of power market and system actors. Economic decisions are made by considering the energy-related judicial documents and the economic measures to identify the most viable investment decisions. Return on investment, discounted payback periods, net present values, and levelized cost of electricity are among the techno-economic metrics which are actively used by investors to make the best decisions for their projects.

The energy policy layer deals with the entire regulatory and legislative framework in the field of energy. Policy makers create legislative and judicial documents to satisfy a state's energy safety and security strategy. All actors on the market are responsible to follow the energy policy and regulatory framework determined and legislated by the policy makers. In the past, centralized and fossil fuel-based power production technologies had dominated the market during the second and third industrial era until the OPEC crisis occurred in the mid-1970s. This global incident had an impact on the entire industry and triggered research and development activities in alternative green energy resources and technologies. Policy makers set ambitious targets associated with climate change to promote the healthy market integration of renewable energy resources. They developed direct and indirect support mechanisms for renewable energy resources to increase their economic feasibility. Recent technological developments in renewable energy sector lowered the initial and operational costs as well as increased the efficiency of the corresponding technologies. Consequently, lowered levelized cost of electricity values helped the renewable energy technologies through competitiveness against their conventional counterparts. In 2017, renewable power capacity surpassed investment volume in fossil-based generating capacity, especially in emerging markets and other economies globally [4].

This paper proposes an alternative techno-political approach which can be applied in future local market mechanisms. In this approach, the policy maker distributes incentive to net energy producers in a local market through the DLT infrastructure. Specifically, we propose two distinct incentive mechanisms which we analyze in detail. Energy policy and regulatory layer players, i.e., the policy makers, may use these new support instruments specially designed to subsidize self-production in the local market domain. For our purposes, energy policy, business, power market and pricing layers are connected using off-chain convention where the associated local market inference is derived using the new energy policy instrument.

The organization of this manuscript is as follows. In Section 2, we provide a literature review of sharing economy, DLT, and local markets as the paradigm, the enabling technology and the domain relevant to our incentive framework. Section 3 is devoted to introducing the local market setting where our approach is valid, and a complete treatment of the market parameters, followed by the derivation of two incentive mechanisms. In Section 4, we demonstrate how the market and incentive mechanisms work through a number of illustrations with resorting to three scenarios. Section 5 is reserved to point out energy policy connotations of this work and our further conclusions.

II. LITERATURE REVIEW: THE PARADIGM, THE ENABLING TECHNOLOGY AND THE DOMAIN

In this section, we provide a literature review on sharing economy, DLT and local energy markets.

A. SHARING ECONOMY

The sharing economy (SE) is an emerging economic paradigm whose drivers are advances in ICT frameworks, differentiation of consumer behaviors who use such technologies, and increasing awareness in sustainability concepts. According to The People Who Share, an UK-based community, global SE volume is estimated to be over £330 billion per year [5]. Within the UK, they report that it is £22,4 billion, and further detail that it amounts to 1,3% of their GDP, although Cheng [6] reports a different global figure as an estimate for 2025 amounting to $335 billion. As in numbers, there is no settled definition of SE, yet there exists many expositions also including diverse terminology for the concept. Among others, for example, Frenken and Schor [7] define it as ''consumers granting each other temporary access to underutilized physical assets (idle capacity), possibly for money'' leaving the sharing of intangibles and services out. In a more encircling definition due to Heinrichs [8] SE involves ''individuals exchanging, redistributing, renting, sharing, and donating information, goods, and talent, either organizing themselves or via commercial organization by social media platforms.'' In relation with particular coincidence to the system we analyze in this manuscript, we prefer to follow the definition by Hamari *et al.* [9] ''the peer-to-peer based activity of obtaining, giving, or sharing access to goods and services, coordinated through community-based online services.'' For a complete discussion of the terminology and alternative definitions one may refer to [10]. Whichever definition one may consort four characteristics are central to the concept of SE: sharing/trading of goods, excess capacity or underutilization, technology-driven collaboration, and user-to-user reciprocal action.

Whereas it is a promising concept with remarkable potential and noteworthy dynamics, a number of criticisms raised with considering different aspects of SE. Frenken and Schor [7] argue that the rise of P2P markets will lead to seizure effects on traditional business volume, and hence a decrease in job opportunities especially for the blue-collar workforce. Lyons and Wearing [11] indicate that SE will result a casualization of workforce without social security coverage considering hosts that lend rooms, in case it becomes their single income channel. Zervas *et al.* [12] note that hotel revenues in Texas declined in areas where a well-known accommodation-sharing platform company is actively sprout coverage.

A powerful driver of adoption and participation in SE is its ecologically sustainable disposition. Hamari *et al.* [9] account that SE may be viewed from the perspectives of sharing, borrowing, reuse and remix, charity, sustainable consumption, and anti-consumption. In this manuscript, we uphold their first and latter two perspectives which translate into P2P energy sharing framework under study as follows. Diffusion of sharing locally produced energy whose source is known to be renewable leads to, less dependence on energy from the utility whose process of generation is unknown leads to, total energy produced whose source is unknown to decline, hence ultimately bring about an expected sustainability impact. Moreover, we also show that this framework bring direct economic benefits to the participants where utility bill of each participant decline.

B. DISTRIBUTED LEDGER TECHNOLOGY AND ENERGY SYSTEMS

DLT is a digital consensus and reliable record-keeping mechanism developed to building trust on a trustless environment such as the internet. DLT accommodates distributed and decentralized digital ledger or depositories within its network. DLT allows the transacted commodity (i.e., service, product, data or payment) to be logged, shared, moved and stored on a special private, public or hybrid network in an immutable manner. Consensus mechanisms are responsible for validation and authentication of DLT operations using special cryptographic functions. Most prominent consensus mechanisms are proof-of-work and proof-of-stake [13].

Smart contracts are digital equivalent of their paper-based counterparts which are designed to facilitate the trust between parties using a special computer code. A smart contract is a computer protocol intended to facilitate, verify, or enforce the negotiation and performance of a contract digitally. Smart contracts allow execution of credible transactions without using third parties. Dynamic execution of smart contracts between the peers can be handy for various use cases where real or almost-real time operations and transactions are needed [14].

DLT has a very high potential to provide for energy domain. More than 300 start-up and spin-off companies initiated various energy blockchain use cases. According to the German Energy Agency [15], DLT can improve efficiency of the existing power system operations and markets, further promoting development of new future energy DLT-based use cases. In a comprehensive energy blockchain perspective report by World Energy Council [16], most popular use cases of DLT in the energy sector are categorized as: decentralized and P2P energy trading, labeling, energy provenance and certification, smart metering and billing, EV charging and payments, and wholesale power trading and settlements.

Wholesale power trading and settlement use cases mainly focus on developing more efficient and applicable autonomous wholesale power trading procedures using DLT.

Settlement of the imbalances in wholesale power markets and grid is a critical task and any deviation between the forecasted and real operations might lead significant monetary penalties. Using DLT and AI-based wholesale trading and imbalance settlement platforms, economic burden on the power systems and markets may be reduced. Decentralized trading, including P2P energy trading use cases, leads the list in terms of number of energy blockchain activities, globally. In this study we also contribute to this track of research, with proposing an alternative approach that has potential to increase the future use of local market based P2P mechanisms by deploying governmental policy support instruments. Smart metering and billing can be considered as one mature application area of energy DLT use cases that can potentially provide considerable cost reductions if the designed system can be operated in the full automated mode. The origin of the energy generated can easily be identified using the DLT framework. As such, labeling, energy provenance and certification, and related energy blockchain use cases serve new opportunities for market players in areas such as renewable energy and carbon certification, and also associated trading platforms. DLT-based EV charging and payment settlement platforms are designed to bring solutions in electro-mobility domain by reducing the additional cost originating from unnecessary third parties, and by optimizing shareable resources.

C. LOCAL ENERGY MARKETS

The current energy landscape and its management faces new challenges due to increasing amount of distributed renewable energy generation, mainly regarding how to comply with this capacity and its decentralized nature. In accordance with this shift, local energy markets, where the participants of market trade energy in close proximity to the location it is originated, are extending into the energy landscape as a new form of marketplace. According to Berka and Cramer [17], these organizations promise substantial benefits for its participants both from economical and environmental aspects, demonstration of the former, on the side, is particular interest in the current manuscript.

Typical participants of a local market are those sellers who have renewable source installed capacity, hence the ability of self-generation; and a group of buyers who lack such self-generation capabilities, thereupon depend on procurement. Participants who supply the local market intend to sell their surplus energy, if available; and their peers are willing to buy their requirement from this surplus. If sold to utility, the surplus energy returns the feed-in tariff per kWh to the supplier. The first group of participants, the so-called *prosumers*, are revenue seekers who pursue a price higher than this tariff for their surplus energy. When bought from utility, the energy will cost utility rate per kWh to the purchaser. The second group of participants who buy from the local market, the so-called *consumers*, are cost pruners who seek for a price which is lower than the utility rate. It is reported that numerous countries are currently in the process of tuning up their energy policies to spur self-consumption of distributed energy generation in this manner [18], [19]. In a review by Jogunola *et al.* [21], local markets are associated with supporting to balance the energy requirements among the participants, minimizing energy loss, reducing energy costs, improving overall reliability, and reducing dependency on the main grid. The dependency issue, on the opposite, been studied from the perspective of reducing the impact of surplus energy on the main grid by Kanchev *et al.* [22].

Realization of above mechanism of the prosumers and the consumers is underpinned by four important enabling technologies. The first one is an energy transmission framework which can operate in consonance to the main grid, called the microgrid. The second one is an energy storage capacity that captures the intermittent generation and fluctuation characteristics of this framework. In this paper however, we do not allow energy to be stored in the local market as it operates. Thus, if there is energy surplus in the system beyond the local trade during any time period, it is cleared by the utility. Our aim is not further investigating the technical aspects and operation characteristics of the microgrids and energy storage systems and we refer the reader to [23] and [24], respectively. The third one is an aggregator entity reprocessing transactions between prosumers and consumers, from there on coordinates the energy sharing and transmission accordingly. We resume introduction of this feature in the next section. To sum up, the last one is a trustworthy and secure ICT platform backing data flow, transactions, contracting and circulation of money between prosumers and consumers.

The DLT and blockchain, which we briefly reviewed in the previous section, are two emerging technologies that reinforce recent progress in local energy markets and their operation. The unalterable and transparent contracting state-of-the-art, the *smart contracts*, including registries of commitments among participants arouse as the participation and transaction structure is grounded in this technology. Inclusive of intermediation to self-generation and self-consumption, the communication, transaction security and essential transparency, Andoni *et al.* [13] point out that DLT and blockchain technologies provide effective setting for automated billing through imbalance settlement.

As the energy sharing and transaction components described above is realized in the local setting, prosumers and consumers then initiate direct energy trading among each other in a peer-to-peer fashion. This trading procedure is known as the *peer-to-peer energy trading* which is independently studied under the aspects of demand response [20], bidding systems [25], cost optimization [26], and minimizing energy sharing losses [27].

III. LOCAL MARKET STRUCTURE AND INCENTIVE MECHANISMS

This section is devoted to describing the local energy market structure, in detail, by means of its pricing mechanism and a thorough discussion of related market parameters. Subsequently, we introduce two fair incentive mechanisms built upon this structure. Yet first, the following points on

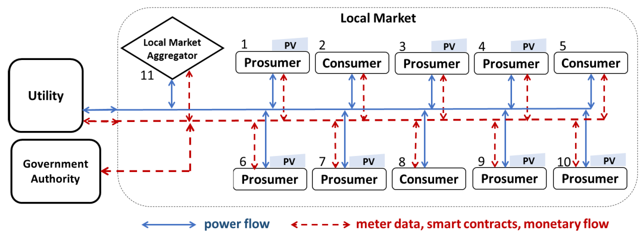

FIGURE 2. An illustrative local market.

market participants and the energy sharing system needs to be clarified.

A. DLT-ENABLED ENERGY SHARING SYSTEM AND ITS PARTICIPANTS

The local energy market we study is a community of prosumers and consumers whose roles are introduced in the preceding section. While the market is functioning, participants trade energy on a P2P basis at any time enabled by the mediating role of the local market *aggregator*. The aggregator, sometimes called the virtual power plant or the energy sharing provider, coordinates energy sharing and transmission between the participants. These actors are equipped with smart devices and communicate through a DLT-based trading platform catering the technology to accommodate transactions and dynamic smart contracts. In this setting, physical energy flow between participants is routed from a shared energy pool by the aggregator instead of a direct node-to-node dispatching pattern. Due to the existence of aggregator's facilitating role, energy sharing and trading over this framework is referred to as *routed P2P energy trading*. This structure is abstracted to a community of ten participants in Fig. 2 for illustration purposes.

The *utility* in this setting refers to a utility provider company. As seen in Fig. 2, there is a bi-directional energy flow between utility and the aggregator indicating that imminent action of the local market with utility grid (i.e., energy trade) is also realized by the aggregator. The *government authority* is an institution of regulatory layer policy maker, which tracks the local market through DLT framework and distributes incentive according to policy under effect.

Transfers of payment and information for the origin of the energy resource can be handled using common blockchain technology frameworks such as *Hyperledger Fabric* and *Ethereum*. The DLT-based local energy trading platform can also be integrated into a larger DLT-based transactive energy platform where critical power system transactions, related operations and payments are managed. Government authority take advantage of the DLT-based platform to track simultaneously origin of electrical power and amount of energy that is locally traded, in order to make sure that the support will be directed to relevant parties accurately.

B. LOCAL MARKET PARAMETERS

Consider a community composed of a set C' of consumers, a set P' of prosumers and let these participants be indexed by i. Further, let t be another index for time periods where the market is functioning. The fact that a participant i is a prosumer does not necessarily imply that it is an active contributor to local energy generation at a given time period t, due to possible excess self energy requirement where its self-consumption exceeds its self-generation. Hence at each time period t, we further divide the set P' to two disjoint sets P_t and M_t, where we denote the set of *net producers* with P_t and the set of *temporary (i.e., makeshift) consumers* with M_t during this period. Thus, a participant $i \in M_t$ is essentially a prosumer yet behaves as a consumer, effective for t, on a temporary basis owing to its net energy requirement during this time period. Hence the set of *net consumers* at t is given by $C_t = C' \cup M_t$. Meanwhile, a prosumer $i \in P_t$ stand with a positive energy surplus during the same time period.

At each time period, we associate participants of the market with two sets of positive values with g_{it} denoting the amount of energy generated and d_{it} denoting the amount of energy demanded by a participant i at t, respectively. Let s_{it} be the surplus energy of participant i at t after its own consumption. We then have:

$$s_{it} = \begin{cases} g_{it} - d_{it}, & \text{if } g_{it} > d_{it} \\ 0, & \text{if } g_{it} \leq d_{it}. \end{cases} \tag{1}$$

Similarly, let r_{it} be the net energy requirement of participant i at t after consuming its own generation, if there is any. Thus, we have:

$$r_{it} = \begin{cases} d_{it} - g_{it}, & \text{if } d_{it} > g_{it} \\ 0, & \text{if } d_{it} \leq g_{it}. \end{cases} \tag{2}$$

Before proceeding to market pricing and derivation of other parameters, we would like to note our convention that the prosumers with $g_{it} = d_{it}$ and hence $s_{it} = r_{it} = 0$ are stationed in P_t for avoiding a possible confusion.

The capability of surplus energy to satisfy the requirement at the market level is an important feature not only it shows the self-generation and self-consumption potential, but will also serve as a sensible basis to facilitate market pricing and related parameters. To this end, we employ a parameter due to [20] called the *supply-demand ratio*, which is defined as the ratio of total energy surplus to the total energy requirement in the local market. We denote the supply-demand ratio at time period t with q_t which is given by [20]:

$$q_t = \frac{\sum\limits_{i \in P_t} s_{it}}{\sum\limits_{i \in C_t} r_{it}}, \tag{3}$$

and hence may alternatively be named as the *surplus-requirement ratio* to conform to our definitions.

Let, p_t be the *local market price* at time period t. We impose minimum and maximum levels for this parameter in accordance to German market rates [28]. We denote German feed-in tariff 12,31 €c/kWh by p_f and define it as a lower limit, whereas we denote German utility price

28,69 €c/kWh by p_u and assign it as an upper limit to p_t. For each time period t, we further define the following parameters: c_{it} is the energy procurement cost of a net consumer i; c_t is reserved to total energy procurement cost of net consumers; u_t is the unit energy procurement cost of each net consumer; y_{it} denotes the revenue (i.e., yield) of a prosumer i; and, z_t is the revenue of the utility.

The above parameters assume different representations due to the altering nature of q_t through t. For this purpose, it is essential that we analyze them according to three possible circumstances as in the following.

1) NO ENERGY SURPLUS IN THE MARKET ($q_t = 0$)

When $q_t = 0$, energy surplus is not available to the local market as $q_t = 0$ implies $s_{it} = 0, \forall i$. Thereby, any net requirement r_{it} must be satisfied from utility grid through the aggregator at the utility price p_u. Then it follows that $p_t = u_t = p_u$ leading to $c_{it} = r_{it} \cdot u_t = r_{it} \cdot p_u$ and hence $c_t = \left(\sum_{i \in C_t} r_{it}\right) \cdot p_u$. On the other hand, $s_{it} = 0, \forall i$ implies $y_{it} = -r_{it} \cdot p_u$. Finally, as all participants are net consumers we obtain $z_t = c_t = \left(\sum_{i \in C_t} r_{it}\right) \cdot p_u$.

2) ENERGY SURPLUS IN THE MARKET PARTIALLY SATISFIES THE REQUIREMENT ($0 < q_t < 1$)

When $0 < q_t < 1$, the total energy surplus in the local market partially satisfies the total requirement. When the energy surplus is limited, the market price tends to be high with an orientation towards p_u:

$$\lim_{q_t \to 0^+} p_t = p_u. \tag{4}$$

On the contrary, when the energy surplus is large, yet still not meeting the total requirement, the market price tends to be low with an orientation towards p_f:

$$\lim_{q_t \to 1^-} p_t = p_f. \tag{5}$$

This mechanism has to be reflected in to the market price-setting. To achieve this, we employ an approach based on the convex combination of two price rates.

Definition 1 (Convex Combination of Two Price Rates): The convex combination of two price rates p_1 and p_2 with coefficient q where $q, 1 - q \geq 0$ is given by:

$$\mathcal{C}(p_1, p_2) = q \cdot p_1 + (1 - q) \cdot p_2 \tag{6}$$

According to the above convention, we use a convex combination of price limits in the market, with employing the surplus-requirement ratio as a coefficient to obtain a market price as follows.

Definition 2 (Market Price at t): The market price at time period t is the convex combination of feed-in tariff and utility price with coefficient q_t and is given by:

$$p_t = \mathcal{C}(p_f, p_u) = q_t \cdot p_f + (1 - q_t) \cdot p_u. \tag{7}$$

When it comes to cost parameters, first note that the individual procurement costs c_{it} must be distributed over the total procurement cost c_t, as net consumers supply their requirements from the energy sharing pool, rather on an individual basis where utility grid is directly attached. Second, we also note that the unit cost of energy procurement u_t is different from the market price p_t, as only a proportion of the net energy requirement in the market is acquired from available surplus. The remaining part is supplied from utility grid through the aggregator at utility price. The total cost of buying the surplus is $\left(\sum_{i \in P_t} s_{it}\right) \cdot p_t$, leaving a remaining energy requirement in the market as $\left(\sum_{i \in C_t} r_{it} - \sum_{i \in P_t} s_{it}\right)$. When bought from utility, this leads to an additional procurement cost of $\left(\sum_{i \in C_t} r_{it} - \sum_{i \in P_t} s_{it}\right) \cdot p_u$. According to these two cost components, the total procurement cost is given by:

$$c_t = \left(\sum_{i \in P_t} s_{it}\right) \cdot p_t + \left(\sum_{i \in C_t} r_{it} - \sum_{i \in P_t} s_{it}\right) \cdot p_u. \tag{8}$$

Each net consumer is bound to its own percentage from this totality with according to its share in the total requirement. Let the term $r_{it} / \left(\sum_{i \in C_t} r_{it}\right)$ be the *share* of a net consumer in the total energy requirement at t. Then it follows that,

$$c_{it} = \frac{r_{it}}{\sum_{i \in C_t} r_{it}} \cdot c_t \tag{9}$$

are the procurement costs for each net consumer at t. The unit procurement cost of net consumers is given by the following property.

Theorem 3 (Unit Procurement Cost at t): The unit procurement cost of net consumers at a time period t is:

$$u_t = \mathcal{C}(p_t, p_u). \tag{10}$$

This unit procurement cost is definitionally equivalent to the *internal buying price* elaborated in Liu *et al.* [20]. However, it is worthwhile to note that these two parameters assume different values since market pricing schemes adopted in the current paper and Liu *et al.*'s [20] study are different. To prevent possible confusion between these two approaches, we conducted a very simple simulation considering increments of 0,1 on the value of $q_t \in [0, 1]$. To simplify the comparison to the reader, we also replaced their original currency unit ¥ to €c. These results are illustrated in Fig. 3.

Moreover, in their fruitful work, Liu *et al.* provide a justification for their internal buying price by resorting to an *economic balance* condition (see, Appendix I in [20]). For this reason, we will not reproduce their approach to prove Theorem 3 here and the reader is referred to this justification. However, we present a simple sketch of proof which is obvious due to our notation without utilizing the economic balance.

Sketch of Proof: We write equation (8) into equation (9) and distribute the term $\left(\sum_{i \in C_t} r_{it}\right)$ to inside denominators to obtain:

$$c_{it} = r_{it} \cdot \left(\frac{\sum_{i \in P_t} s_{it}}{\sum_{i \in C_t} r_{it}} \cdot p_t + \frac{\sum_{i \in C_t} r_{it} - \sum_{i \in P_t} s_{it}}{\sum_{i \in C_t} r_{it}} \cdot p_u \right), \tag{11}$$

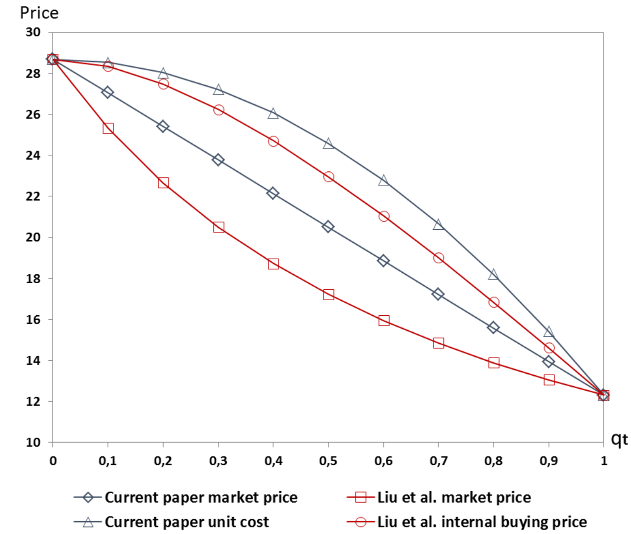

FIGURE 3. A comparison of market and procurement pricing.

which, according to the definition of q_t, is equal to:

$$c_{it} = r_{it} \cdot (q_t \cdot p_t + (1 - q_t) \cdot p_u), \tag{12}$$

and further reduces to $c_{it} = r_{it} \cdot \mathcal{C}(p_t, p_u)$. Its equivalence with $c_{it} = r_{it} \cdot u_t$ shows $u_t = \mathcal{C}(p_t, p_u)$. □

Finally, the revenue of a prosumer is dependent on whether it is a net producer or a temporary consumer at t, and is given by:

$$y_{it} = \begin{cases} s_{it} \cdot p_t, & \text{if } i \in P_t \\ -\dfrac{r_{it}}{\sum_{i \in C_t} r_{it}} \cdot c_t, & \text{if } i \in M_t. \end{cases} \tag{13}$$

Utility's revenue, on the other hand, amounts to:

$$z_t = \left(\sum_{i \in C_t} r_{it} - \sum_{i \in P_t} s_{it} \right) \cdot p_u. \tag{14}$$

3) AMPLE ENERGY SURPLUS IN THE MARKET ($Q_T \geq 1$)

When $q_t \geq 1$ the energy surplus in the local market is abundant and completely satisfies the total requirement. Once the total requirement is satisfied, the remaining surplus is sold to utility grid through the aggregator. Hence, net consumers qualify procuring their requirements over the feed-in tariff as well. This means we have $p_t = u_t = p_f$, and hence $c_{it} = r_{it} \cdot u_t = r_{it} \cdot p_f$ leading to a totality of $c_t = \left(\sum_{i \in C_t} r_{it}\right) \cdot p_f$. Prosumers are dependent to the same rate, thus we obtain:

$$y_{it} = \begin{cases} s_{it} \cdot p_f, & \text{if } i \in P_t \\ -r_{it} \cdot p_f, & \text{if } i \in M_t. \end{cases} \tag{15}$$

Accordingly, utility's revenue is given by:

$$z_t = -\left(\sum_{i \in P_t} s_{it} - \sum_{i \in C_t} r_{it} \right) \cdot p_f. \tag{16}$$

Before coming to an end to our discussion of local market parameters, we would like to present two more features that may be of particular use to facilitate automated billing. The account balances of participants we introduce below are accumulated cost and revenue functions that serve for this purpose. Let, $c^b_{it^*}$ be the *account balance of a consumer i* at a given time period t^*, which may be constructed as:

$$c^b_{it^*} = -\sum_{t=0}^{t^*} c_{it}. \tag{17}$$

Similarly, let $y^b_{it^*}$ be the *account balance of a prosumer i* at a given time period t^*. This is also given by:

$$y^b_{it^*} = \sum_{t=0}^{t^*} y_{it}. \tag{18}$$

C. INCENTIVE MECHANISMS

In this section, we derive two incentive mechanisms favoring net producers that supply surplus energy to the local market. The government authority whose role is discussed in Subsection A provides incentive whenever there are net producers, hence available surplus energy, in the local market. We define a *stipend* p_s in terms of €c/kWh to be distributed to net producers by the government authority. This stipend results an alteration in the unit revenue of net producers, which naturally, is equal to the market price when the incentive mechanism is not in effect. We call this unit revenue the *incentivized price*. The first incentive mechanism is based on a fixed stipend, whereas in the second mechanism we consider a decaying stipend for our purposes.

1) INCENTIVE WITH A FIXED STIPEND

In this mechanism net producers are allowed to receive a fixed stipend p_s for their entire trade when $0 < q_t < 1$. Beyond this limit where $q_t \geq 1$, only the proportion of their trade that is realized within the local market is incentivized, whereas the proportion carried out with the utility is not incentivized. Since the government authority continues to favor the local trade component with the stipend in effect, we call it a fixed stipend.

When $0 < q_t < 1$, the fixed stipend is appended to the market price to obtain the incentivized price. Let p_t^+ be the incentivized price at t for $0 < q_t < 1$ with the superscript denoting that the entire trade of net producers is incentivized. We have $p_t^+ = p_t + p_s$ resulting the following adjustment to calculation of revenues for prosumers due to the incentive distributed to net producers:

$$y_{it} = \begin{cases} s_{it} \cdot p_t^+, & \text{if } i \in P_t \\ -\dfrac{r_{it}}{\sum_{i \in C_t} r_{it}} \cdot c_t, & \text{if } i \in M_t. \end{cases} \tag{19}$$

When $q_t \geq 1$, since the P2P trade within the participants is still incentivized, it needs to be apportioned over the total trade in order to maintain a sensible incentivized price. Let p_t^- be the incentivized price at t for $q_t \geq 1$ with the superscript denoting that the trade of net producers is partially incentivized. We obtain this parameter due to the following theorem.

Theorem 4 (Fixed Stipend Incentivized Price for $q_t \geq 1$): The incentivized price at time period t when $q_t \geq 1$ is:

$$p_t^- = \mathcal{C}(p_t^+, p_f) \tag{20}$$

with coefficient $1/q_t$.

Proof: Note that the revenue obtained by net producers at time period t by satisfying the total requirement at the local market is $\left(\sum_{i\in C_t} r_{it}\right) \cdot p_t^+$. On the other hand, the revenue they attain by selling the remaining surplus to the utility is given by $\left(\sum_{i\in P_t} s_{it} - \sum_{i\in C_t} r_{it}\right) \cdot p_f$. Hence the total revenue of net producers amounts to:

$$\left(\sum_{i\in C_t} r_{it}\right) \cdot p_t^+ + \left(\sum_{i\in P_t} s_{it} - \sum_{i\in C_t} r_{it}\right) \cdot p_f. \tag{21}$$

When apportioned to each net producer according to its share $s_{it}/\left(\sum_{i\in P_t} s_{it}\right)$ in the total trade this gives the revenue of a net producer i:

$$\frac{s_{it}}{\sum\limits_{i\in P_t} s_{it}} \cdot \left(\left(\sum_{i\in C_t} r_{it}\right) \cdot p_t^+ + \left(\sum_{i\in P_t} s_{it} - \sum_{i\in C_t} r_{it}\right) \cdot p_f\right) \tag{22}$$

which, in case, the first $\left(\sum_{i\in P_t} s_{it}\right)$ term is distributed to inside denominators leading to:

$$s_{it} \cdot \left(\frac{\sum_{i\in C_t} r_{it}}{\sum_{i\in P_t} s_{it}} \cdot p_t^+ + \frac{\sum_{i\in P_t} s_{it} - \sum_{i\in C_t} r_{it}}{\sum_{i\in P_t} s_{it}} \cdot p_f\right). \tag{23}$$

Finally, resorting to the definition of q_t, we obtain:

$$s_{it} \cdot \left(\frac{1}{q_t} \cdot p_t^+ + \left(1 - \frac{1}{q_t}\right) \cdot p_f\right), \tag{24}$$

which is equal to $s_{it} \cdot \mathcal{C}(p_t^+, p_f)$ whose further equivalence with $s_{it} \cdot p_t^-$ proves the theorem for $q_t \geq 1$. □

Accordingly, we implement the following adjustment to the calculation of revenues for prosumers when $q_t \geq 1$:

$$y_{it} = \begin{cases} s_{it} \cdot p_t^-, & \text{if } i \in P_t \\ -\dfrac{r_{it}}{\sum_{i\in C_t} r_{it}} \cdot c_t, & \text{if } i \in M_t. \end{cases} \tag{25}$$

Pricing by fixed stipend incentive mechanism is illustrated in Fig. 4 where incentivized prices over increments of 0,1 on the value of $q_t \in [\varepsilon, 2]$ are depicted with considering fixed stipends of 2, 6 and 10 €c/kWh, respectively. Since these prices are not defined when $q_t = 0$, we considered a very small number ε to initiate the graph. As recognizable from this graph, incentivized prices are in parallel to the market price by a residual that equals to the corresponding stipend until $q_t = 1$. After this point as q_t increases, they tend to approach to feed-in tariff p_f due to the distribution of incentive, which allotted only to the local trade component.

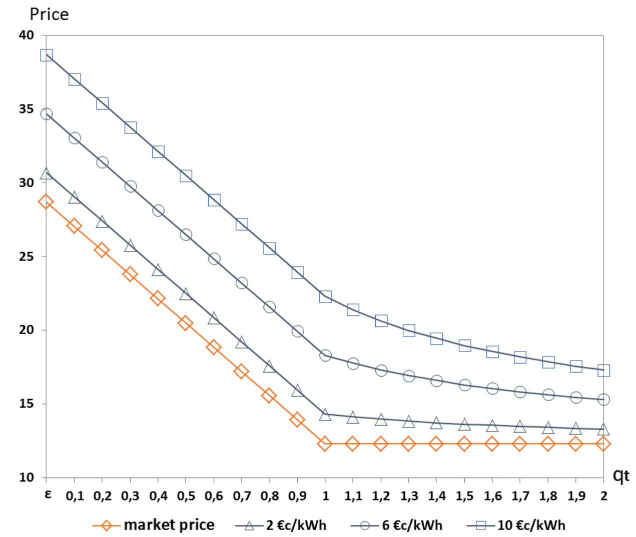

FIGURE 4. **Pricing by fixed stipend incentive mechanism.**

2) INCENTIVE WITH A DECAYING STIPEND

In this mechanism, as opposed to a fixed stipend, net producers are endowed with a stipend appended to the market price which decreases as q_t increases, and extincts when $q_t = 1$. In other words, when surplus energy is limited net producers receive a large stipend, and when it is substantial they receive a modest stipend. The stipend attains a value of 0 at $q_t = 1$ and phases out, beyond which, as opposed to the fixed stipend, the government authority discontinue distributing it. Due to this aspect, we call the following procedure a decaying stipend incentive mechanism.

Since the incentive mechanism is only in effect when $0 < q_t < 1$, we construct a single incentivized price p_t^+ as follows. First note that, due to decaying stipend, the incentivized price decreases as q_t increases. To reflect this, we consider a decay model with base e where:

$$p_t^+ \propto e^{-q_t}. \tag{26}$$

With bringing in two constant terms k_0 and k_1, we construct the decay model we will utilize for incentivized price as follows:

$$p_t^+ = k_0 \cdot e^{-k_1 \cdot q_t}. \tag{27}$$

The following theorem establishes the incentivized price.

Theorem 5 (Decaying Stipend Incentivized Price): The incentivized price for decaying stipend incentive mechanism at time period t is given by:

$$p_t^+ = p_t^{q_t} \cdot (p_t + p_s)^{1-q_t} \tag{28}$$

with $q_t > 0$.

Proof: Net producers immediately start receiving stipend when at least one of them provide with surplus energy. Thus, by considering the decay model (27) we write:

$$\lim_{q_t \to 0^+} k_0 \cdot e^{-k_1 \cdot q_t} = p_t + p_s, \tag{29}$$

which gives $k_0 = p_t + p_s$. On the contrary, when they attain the extend to fully satisfy the total requirement at the local market the stipend vanishes. In this case, we consider:

$$\lim_{q_t \to 1^-} k_0 \cdot e^{-k_1 \cdot q_t} = p_t. \tag{30}$$

Accordingly, we obtain:

$$(p_t + p_s) \cdot e^{-k_1} = p_t \tag{31}$$

$$e^{-k_1} = \frac{p_t}{p_t + p_s}, \tag{32}$$

which after resorting to ln function gives k_1:

$$\ln e^{-k_1} = \ln\left(\frac{p_t}{p_t + p_s}\right) \tag{33}$$

$$-k_1 = \ln\left(\frac{p_t}{p_t + p_s}\right). \tag{34}$$

Hence, the incentivized price at t is given by:

$$p_t^+ = (p_t + p_s) \cdot e^{\left(\ln\left(\frac{p_t}{p_t+p_s}\right)\right)\cdot q_t} \tag{35}$$

$$= (p_t + p_s) \cdot e^{q_t \cdot \ln\left(\frac{p_t}{p_t+p_s}\right)} \tag{36}$$

$$= (p_t + p_s) \cdot e^{\ln\left(\frac{p_t}{p_t+p_s}\right)^{q_t}} \tag{37}$$

$$= (p_t + p_s) \cdot \left(\frac{p_t}{p_t + p_s}\right)^{q_t} \tag{38}$$

$$= p_t^{q_t} \cdot (p_t + p_s)^{1-q_t}. \tag{39}$$

This proves the theorem. □

Finally, calculation of revenues for prosumers is same as the fixed stipend counterpart with the exception of the incentivized price:

$$y_{it} = \begin{cases} s_{it} \cdot p_t^+, & \text{if } i \in P_t \\ -\dfrac{r_{it}}{\sum_{i \in C_t} r_{it}} \cdot c_t, & \text{if } i \in M_t. \end{cases} \tag{40}$$

Pricing by decaying stipend incentive mechanism is illustrated in Fig. 5 on the same setup prepared for the fixed case, except for q_t where we considered $q_t \in [\varepsilon, 1{,}5]$. The incentivized prices start at neighborhoods to respective limits $p_t + p_s$ due to ε, from where stipends and hence the incentivized prices, decay to the extent $q_t = 1$. This is the point where all the stipends are distributed and incentivized prices degenerate into the feed-in tariff. Beyond this point, incentive mechanism is not in effect.

IV. ILLUSTRATION OF THE MARKET PARAMETERS AND INCENTIVE MECHANISMS

In this section we illustrate how the market parameters and the incentive mechanisms work by utilizing three scenarios. Before that, we present a few remarks on the representative local market where we experimented all the formulations and incentive mechanisms.

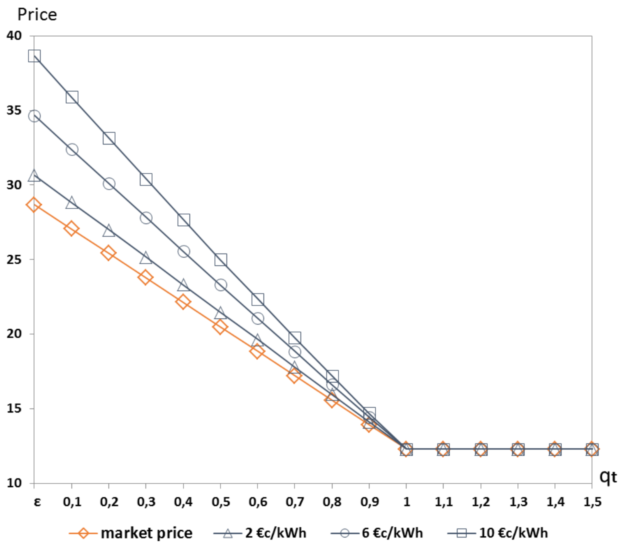

FIGURE 5. Pricing by decaying stipend incentive mechanism.

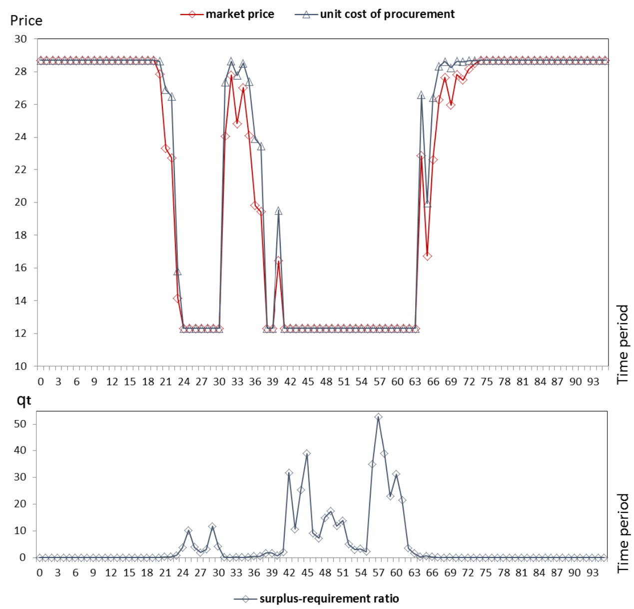

FIGURE 6. Market price, surplus-requirement ratio, and corresponding unit procurement cost of net consumers.

A. A LOCAL MARKET AS A TEST BED AND SCENARIO PLANNING

To demonstrate the working principles of the market parameters and incentive mechanisms, we considered a local market with 10 participants and an aggregator whose structure is presented in Fig. 1. In this community, there are 7 prosumers with installed PV capacity which can supply the market, and 3 consumers with no such capabilities. To equip these participants of the local market with realistic energy profiles we used the CREST demand model tool [29]. A single day profile is generated with using 15 minute time intervals.

Subsequently, we considered three distinct scenarios for illustration purposes which may be defined as follows:

Scenario 1: (Base) The market functions for one day where no incentive mechanism is in effect.

Scenario 2: (Fixed) The market functions for one day where the government authority stimulates the market with fixed stipend incentive mechanism.

Scenario 3: (Decaying) The market functions for one day where the government authority stimulates the market with decaying stipend incentive mechanism.

We experimented with this test bed by running it for 24 hours starting at midnight 00:00 until again reaching midnight the next day leading to a planning horizon where we have $t = 0, \ldots, 95$. The above routine is repeated for all three scenarios we considered.

B. ILLUSTRATION OF MARKET PARAMETERS

We now provide illustrations for market parameters which, except for y_{it} and y_{it}^b, does not depend on the scenario in effect. Hence, we prefer to use the base scenario in this section. However, we reinstate y_{it} and y_{it}^b under other scenarios again in the next section.

1) MARKET PRICE, SURPLUS-REQUIREMENT RATIO AND THE UNIT PROCUREMENT COST

Fig. 6 illustrates market price and unit procurement cost depicted over the surplus-requirement ratio. As seen from this figure, $p_t = p_u$ all through the night where $q_t = 0$ and there is no PV energy generation, hence no surplus. Then, early in the morning as q_t advance p_t drops to p_f, yet just before noon morning energy requirement at the market peaks where q_t fluctuate close to 0. This is when p_t also peaks to the benefit of net producers. Through afternoon there is ample surplus due to high generation assured by the elevated values of q_t, which is more than enough to push p_t to p_f. However q_t is in a sharp decline at late afternoon where p_t advances to climb p_u level again, where it will stay through night time due to $q_t = 0$. The unit cost of procurement, on the other hand, diverge from $p_t = 0$ at time periods where energy surplus partially satisfies the total requirement at the market level. Otherwise, it is adjoined with p_t to follow p_f or p_u.

2) PROCUREMENT COST OF A CONSUMER, REVENUE OF A PROSUMER AND ACCOUNT BALANCES

To demonstrate these parameters we picked Prosumer 1 and Consumer 2 to serve as two representative participants of the local market previously introduced in Fig. 2. Account balance of Consumer 2 depicted over corresponding procurement cost incurred at each time period t is illustrated in Fig. 7. Consumer 2 is a steady energy purchaser with only a single high peak at the procurement cost that coincide with the plunge of the market price at late afternoon in the preceding section. The account balance is on a constant fall according to continual energy requirement by this consumer. At the end of the day, Consumer 2 accumulated a cost of €4,76.

On the other hand, account balance of Prosumer 2 depicted over corresponding revenue obtained at each time period t is illustrated in Fig. 8. Prosumer 1 starts the day with net energy requirement resulting successive negative revenue values that drive the account balance to slide mildly on the negative side.

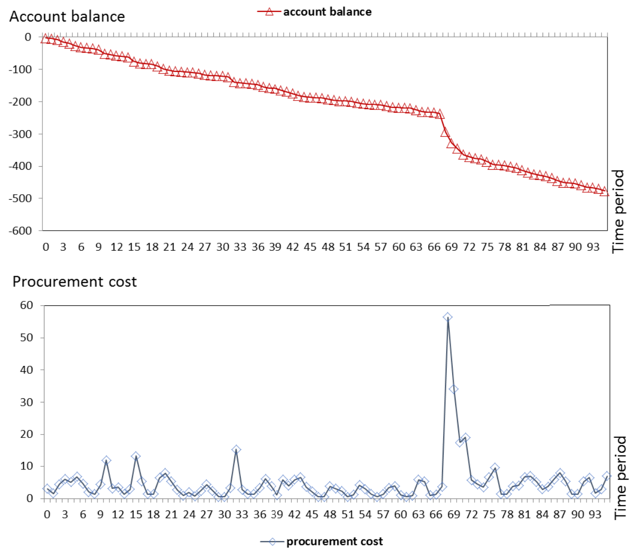

FIGURE 7. Procurement cost and account balance of consumer 2.

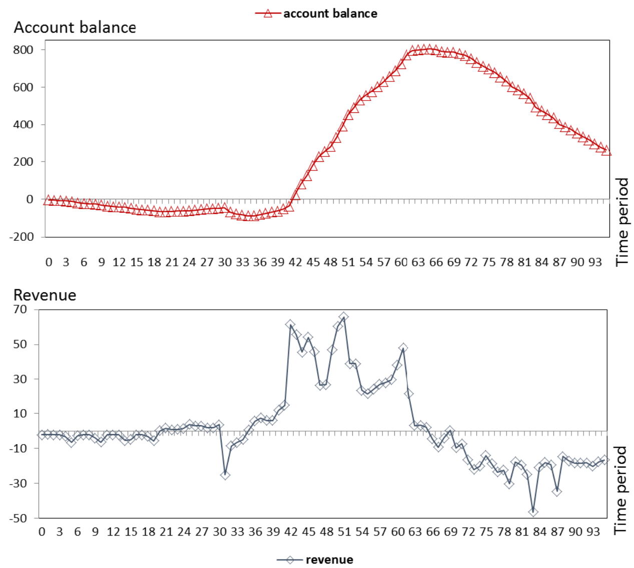

FIGURE 8. Revenue and account balance of prosumer 1.

Yet, when self-generation is in place Prosumer 1 attains considerable revenue levels which drive the account balance to an upsurge as high as €8,04. At night time when the self-generation sets out, Prosumer 1 is a net consumer incurring the procurement cost effective in the market. Nevertheless, this results to end the day with a positive balance on the account that accumulated to €2,61.

3) REVENUE OF THE UTILITY

The utility is a constant revenue collector, yet our aim here does not include its balance settling with the government authority and once all requirements at the local market is satisfied, we let utility collect surplus energy from net producers in its own expense. Hence, we allow the utility revenue assume negative values as illustrated in Fig. 9. Generally, it crumples to negative values when there is ample surplus

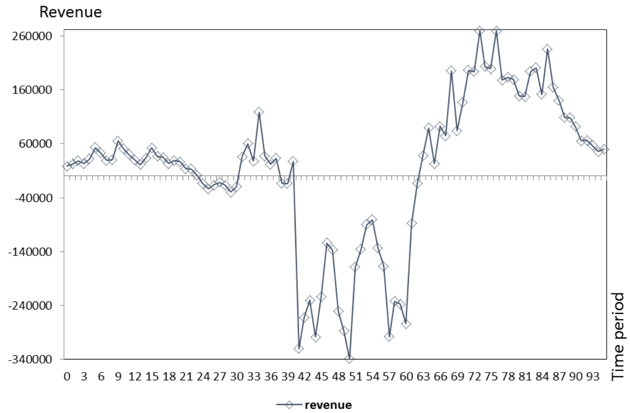

FIGURE 9. Revenue of utility.

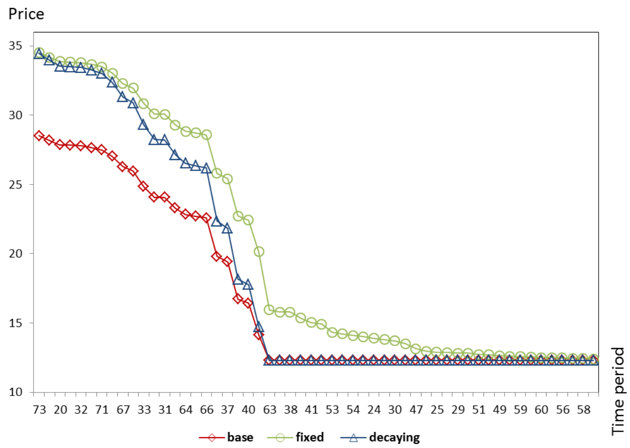

FIGURE 10. Market and incentivized prices.

in the market and expands to positive values when the market rely on utility for its requirement.

C. ILLUSTRATION OF INCENTIVE MECHANISMS

In this section we illustrate incentivized price levels that occur in the local market during one day. Subsequently, we show the effect of incentive mechanisms on prosumer revenue, and finally to prosumer account balance with again resorting to Prosumer 1. For this purpose, we carried out the experiment independently for fixed and decaying scenarios with allowing an arbitrary stipend of 6 €c/kWh for two scenarios and obtained the following results.

1) INCENTIVIZED PRICES

We calculated the incentivized prices for two scenarios where incentive mechanisms are in effect while the price for base scenario equals the market price. It is confusing to depict them simply on market price, as for some time periods incentivized prices are not defined due to $q_t = 0$. Hence, for the sake of clarity we sorted out those periods where incentive is not defined and ordered the data in increasing order of q_t with keeping their original time period labels. The resulting graph is illustrated in Fig. 10. As seen from this figure, in the decaying scenario, the incentivized price adjoin the market price where the 6 €c stipend vanishes at time period labeled with # 63. This also marks the first point with $q_t \geq 1$ where q_t cuts the level $q_t = 1$ upwards in the arrangement. Beyond this point, the incentivized price follows the market price as incentive is not distributed. On the contrary, incentivized price in fixed scenario keep the 6 €c stipend at the same time period, yet after this point, it steadily approaches to the market price due to the apportionment of incentive offered to local trade, to the total trade. At time periods with large q_t, for example # 56 and # 58, it almost levels with p_f due to high volume of surplus energy traded in these periods.

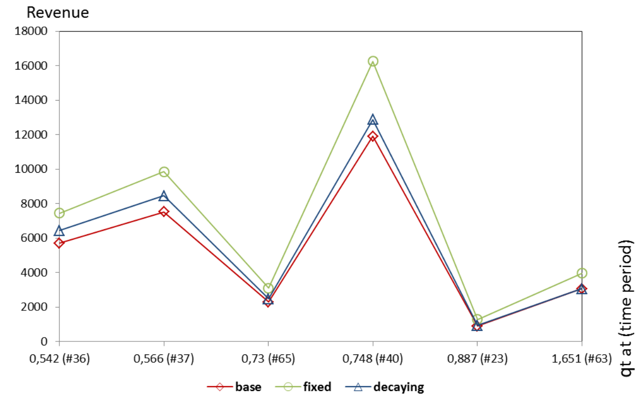

FIGURE 11. Incentivized revenue of prosumer 1 at $q_t \in (0{,}542, 1{,}651)$.

2) INCENTIVIZED REVENUE OF A PROSUMER AND ACCOUNT BALANCE

For our purposes we again single out Prosumer 1, and similarly to the previous section, we sorted out those time periods where incentive is not defined with ordering the data in increasing order of q_t. This arrangement just separates the incentivized revenue, which we aim to show in this part of the argument, from the revenue generated without the incentive. Yet, we will invert it back when studying the account balance because Prosumer 1 is a net consumer at that detail and its revenue assume negative values. Price behavior loses visibility as we depict all the graph, hence we prefer to illustrate two important local parts out of it. To this aim, we first illustrate incentivized revenue generation of this prosumer at surplus-requirement ratio interval $q_t \in (0{,}542, 1{,}651)$ at Fig. 11 whereas time labels for q_t values are kept appended in brackets. As seen from this figure, fixed scenario deliver larger revenues since the stipend is anchored. However, as q_t increases the revenues rewarded by the decaying scenario slightly converge to revenues at the base scenario as the stipend fade away. It is recognizable that, once q_t tears up the $q_t = 1$ level, revenues for decaying scenario and base scenario merge, as fixed scenario revenue diverges marking the continuous support from the government authority.

The second part of the Prosumer 1 incentivized revenue graph, illustrated in Fig. 12, represents the extreme levels of q_t transpired during the experiment where surplus energy is traded in large amounts. Since decaying scenario does not award incentive beyond $q_t \geq 1$, in this graph revenues for

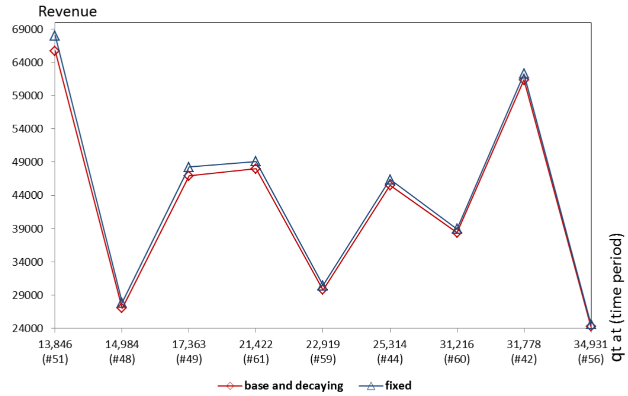

FIGURE 12. Incentivized revenue of prosumer 1 at large q_t levels.

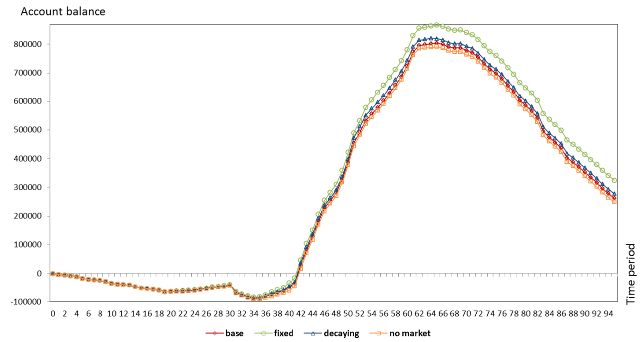

FIGURE 13. Account balance of prosumer 1 under three scenarios.

base and decaying scenarios are shown as merged. Clearly, as q_t increases revenues for fixed scenario converge to the revenues for base and decaying scenarios.

The account balance of Prosumer 1 is illustrated in Fig. 13 considering three scenarios. As seen from this Figure, decaying mechanism is a mediocre performer with its altering stipend tuned according to q_t levels resulting significantly lower revenues when compared to its fixed counterpart. In decaying scenario, balance of Prosumer 1 is quite better than base scenario and accumulated a mere €2,66 at the end of the day. However, keeping the stipend fixed pays off to Prosumer 1 better, given by the significant accumulation in the account balance as seen in Fig. 13. Prosumer 1 was able to complete the day with €3,24 under the fixed scenario.

V. ENERGY POLICY CONNOTATIONS AND CONCLUSIONS

The significance of DLT opened a new avenue of research where various use cases are investigated to conclude whether their decentralized business model or the centralized counterpart is better. To this end, consider once a case where local market is not formed, hence the participants engage with the utility individually. We generated Prosumer 1 account balance under this case using the same daily sample profile and the result is appended to Fig. 13. It is clearly an inferior alternative to the decentralized complement where Prosumer 1 accumulates €2,47 when compared to €2,61 conceivable in a decent local market mechanism under this sample daily profile. When it comes to Consumer 2, the balance is negatively affected and in sharp decline from €-4,76

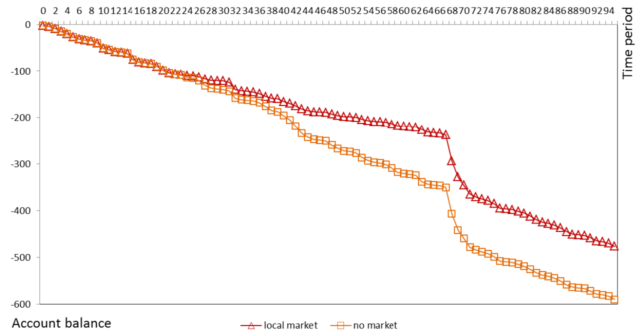

FIGURE 14. Account balance of Consumer 2: Centralized vs. decentralized setting.

calculated for decentralized structure to €-5,90 when there is no local market for the same sample daily profile. For completeness, this is illustrated in Fig. 14. Evidently, decentralized local market structure favors its participants and they are better off than acting individually.

Proposed DLT-based organization also allows deploying new support mechanisms as demonstrated by two incentive schemes in this paper. Energy policy, business, power market and pricing layers of the energy system can be linked using off-chain convention, as illustrated in Fig. 1, to implement and execute such new energy policy instruments. By doing so, the economic viability of behind-the-meter renewable energy resources, as well as benefits to such system owners will increase. Potentially, the amount of locally produced and consumed energy will increase, and therefore, economic losses associated with the transmission of electricity will decrease.

Price based incentives such as feed-in tariff and flexible grid access are mainly utilized to reduce the cost related hurdles by enabling favorable pricing for renewable energy resources. Feed-in tariff is designed to reduce the cost of energy from specific renewable energy generation technologies based on generation amount where the minimum price is guaranteed. On the other hand, net metering or flexible grid access allows electricity flow on two directions and associated payment transactions are only settled for consumers' net energy use. The energy policy instrument proposed in the current manuscript serves as a hybrid incentive method which combines feed-in tariff and flexibility grid access type of mechanisms using the advantage of distributed ledger technology. We strongly believe that the incentive mechanisms we proposed and alike will accelerate diffusion of decentralized local market structures and enable a number of possible future use cases under this promising domain of the contemporary energy systems.

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