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Novel Donation Sharing Mechanisms Under Smart Energy Cyber-Physical-Social System and DLT to Contend the Energy Poverty Problem

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ABSTRACT The objective of this study is to introduce a new use case under smart energy cyber-physical-social system (CPSS) that brings together the competence of distributed ledger technology (DLT) and essence of peer-to-peer local energy markets. This use case involves donation sharing under a DLT-based charity system to support financially-disadvantaged citizens in covering their residential energy requirements in an anonymous and effective manner, as a means to contend the notorious energy poverty problem. Essential architecture and processes for such a sharing concept are discussed by adopting a layer-based representation of the smart energy CPSS. Fundamental step-by-step interactions among its functional layers for realizing prospective social welfare benefits are illustrated. Based on this framework, two distinct donation sharing mechanisms that work under a DLT-empowered local market setting are proposed. Operation of these donation sharing mechanisms are illustrated on a local energy market with resorting to a sample daily energy profile and a series of hybrid scenarios. Effect of donation sharing on accounts of market participants and charity system are detailed.

INDEX TERMS Energy poverty, blockchain, distributed ledger, cyber-physical-social system, peer-to-peer energy trading, local energy market.

I. INTRODUCTION

Energy services are those ‘‘benefits that energy carriers produce for human well-being’’ [1]. Basically, we shall recount space heating and cooling, water heating, lightning, cooking and refrigeration within the scope of such services which allow people to stay healthy and secure. In a thorough view, the services that relate to use of information technology and modern appliances are added to this list as these allow people to better maintain their professional life and enable integration into social life. For a typical household, deprivation of such services imply not having appropriate access or being able to sustain reaching them within reasonable financial means. This leads to the condition what is known as the *energy poverty*.

Energy poverty is described as ‘‘the inability to attain socially and materially necessitated levels of domestic energy services’’ [2], such as the ones listed above. It is a serious condition with noxious effects on ‘‘personal health, safety, household income and labor productivity’’ [3]. It has been extensively reported that energy poverty incite within grounds such as low levels of electrification, high energy prices, low household income, economic underdevelopment, counterproductive institutions, and lack of energy efficiency [4]–[6]. Though may be first deemed a developing world problem when typical supply-side and grid extension difficulties are considered, energy poverty is indeed a prevailing developed world problem due to its multi-dimensional and complex origins. It is estimated in the European Union (EU) that a substantial population of 44,5 million live in energy poverty [7]. What is more is that energy poverty in the EU severely disrupt energy transitions of even the leading members of the union, see eg. the case of Germany [8]. Therefore, EU is concerned about this urgent problem and trying to develop countermeasures to deal with it considering the EU parliamentary requirements and country-based policy definitions which differentiate in features such as the social and energy policies, tariff and subsidy policies, and energy efficiency policies [9], [10].

Having highlighted the urgent status of the energy poverty problem, in the remainder of this manuscript we demonstrate novel donation sharing mechanisms to tackle it within

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contemporary transactive energy systems. This case essentially involves donation sharing in local peer-to-peer (P2P) energy markets for the purpose of covering residential energy requirements of a set of financially disadvantaged households, i.e. the donation recipients, under a distributed ledger technology (DLT) based charity system.

This study is well placed to address two gaps in the current literature of energy poverty. First, a considerable share of this body of knowledge focused on the developing world energy access problem [5], [11]–[13], and as primary means to provide for that, the grid expansion issue [14]. However, the main problem with energy poverty that well transpire in the developed world is the *affordability* problem, and studies that concentrate on this problem are rare [15]. In this work, we directly aim the affordability problem and try to show how to relieve residential energy costs, which devour substantial proportions of household income of the financially disadvantaged, with covering such requirements through donation sharing. Second, among the studies that put energy poverty on the spotlight, those stressing the potential of distributed generation and renewable energy investments are limited [16]. Accordingly, in the current account we aim to promote a distributed generation/resource pooling perspective as effective means to help alleviating the energy poverty. In fact, in a relevant study, when considering specific measures to counter the energy poverty problem it was explicitly suggested that they "…may include supporting neighbourhoods, regions to address domestic energy deprivation with affordable and locally-sourced low-carbon energy, as well as ensuring the pooling of household resources via various informal or formal networks so as to reduce individual energy needs" [6]. This suggestion is deeply related to what is studied in this manuscript. Specifically, we develop two novel mechanisms suitable for donation sharing in local energy markets characterized by distributed renewable energy generation and P2P energy trading over a community micro-grid. These mechanisms operate through a DLT-based charity system that brings together both external contributors, i.e. anonymous citizens that organize online and collaborate socially for a common good; and, internal contributors, i.e. participants with different roles from the local energy market itself.

The first donation sharing mechanism is what we call *external donation sharing* where donation is provided by the charity system directly to cover the energy requirements of donation recipients in the local market. Subsequently, we introduce another donation sharing mechanism we named as the *internal donation sharing* where energy requirements of the donation recipients are supplied within the local market and associated financial encumbrance is shouldered by volunteering market participants. Through these two discussions, we completely analyze market pricing and essential market dynamics such as the distribution of energy procurement costs to consumers in order to obtain unit procurement costs, revenue generation of prosumers, and participant account balances associated with such cost/revenue accumulation. We provide computational experiments to illustrate the effect of donation sharing to accounts of the charity system and market participants by resorting to a series of hybrid scenarios both considering local market conditions and complement cases where local market is not formed and market participants engage in direct energy trading with the utility grid.

To this end, we delineate contemporary energy system as a cyber-physical-social-system (CPSS) and prefer to describe this new use case under such framework. Combination of the cyber space, physical space and social space; in very basic terms, integration of *computers*, *humans* and the *things* create hybridized systems for social use named the CPSS. The main functionality of a CPSS is to uncover people's needs in the social context and provide proactive service in the physical world. Therefore, according to our convention, smart energy systems are multi-layer complex CPSS whose functionalities may be organized in eight distinct layers as illustrated in Figure 1. In this representation, social space contains social welfare, energy policy & regulatory, business, and power markets & pricing layers; cyber space accommodates control & optimization, information & data, and communication layers; lastly, physical space involves the power system layer. Discussion of essential tasks of donation sharing that were realized at these layers is left to a separate section in this paper.

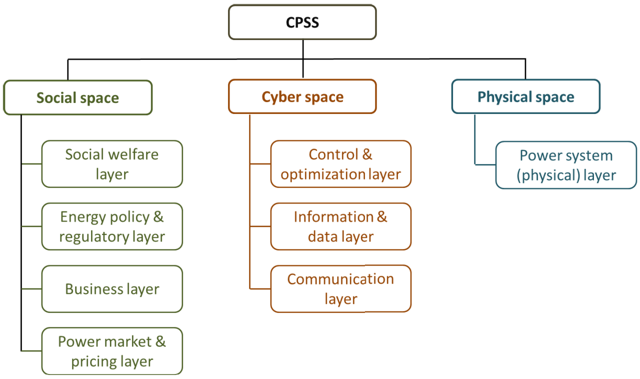

FIGURE 1. Energy system as a multi-layer CPSS.

We strongly believe that this new use case is a fruitful contribution to the literature from four aspects. First, it is an uncomplicated and practical approach countering the energy poverty problem from the less-studied affordability perspective in comparison to the energy access/grid expansion axis. Second, it is a good example highlighting the true potential of distributed generation and use of locally-sourced renewable energy regarding this problem. Third, it is a novel concept that features the resource pooling prospect that is not yet placed in the energy poverty literature. Fourth, it illustrates an interesting case of energy system digitalization where capabilities of DLT are efficiently utilized in both donation sharing mechanisms to distribute subject endowment in a secure as well as rapid way.

In particular, four desirable aspects of the DLT were important to our purposes when designing these mechanisms. First of all, it provides a secure and trustable transaction component for the whole energy CPSS. Second, it assumes a tamper-proof environment for monetary flow between parties in the system (eg. donation contributors, charity, local market participants, donation recipients and the utility). Third, it allows execution of smart contracts due stipulated conditions between market participants at the local level. And fourth, it admits utilizing smart metering devices at each node, i.e. market participants, of the local micro-grid under study.

Both donation sharing mechanisms, in our view, demonstrate promising models on how ordinary citizens may be organized within a CPSS to involve in contending similar social welfare problems. The predicament of energy poverty and essence of the DLT and CPSS are integral to further elaborating this use case. As such, the remaining part of this manuscript start with a very brief overview of this subject literature in Section 2. Section 3 is reserved to an architectural description of donation sharing use case where the main processes, interactions between layers of the energy CPSS, and necessary utilization of the DLT network in on-chain and off-chain conventions are explained. Section 4 is devoted to introducing external and internal mechanisms to donation sharing in local energy markets and mathematical derivation of relevant market parameters under P2P energy trading framework. Section 5 involves computational experiments to illustrate effects of external and internal donation sharing to charity and market participant accounts, respectively. Finally, Section 6 includes our conclusions to this study.

II. LITERATURE REVIEW

According to Birol [17], there exist three major challenges in the coming decades to the global energy system. These are the growing risk of disruptions to energy supply, environmental damage problem due to energy production and use, and persistent energy poverty. Energy poverty is a term linked to a set of fundamental problems in insufficient energy access [13], [18]; futile operation of socio-technical systems to fulfill household energy requirements [6], [19]; incompetent energy efficiency [20] and the affordability [15].

The driving force to energy services variety is the needs of the household. Pereira *et al.* [12] find out that rural electrification leads to a rapid change in consumption profiles and a reduction of the energy poverty. Though, the case is different for urban settings. Bouzarovski and Petrova [6] note that satisfaction of diverse needs is an important factor that enable people to carry out their everyday activities and attain well-being, and therefore, approaching the energy poverty problem considering basic needs does not fully represent actual requirements of today's typical household. Bazilian *et al.* [19] examined how efficiently current energy governance systems operate to answer the needs of the financially disadvantaged in particular. In a similar line, Buzar [21] developed a geographic interpretation of the energy poverty in eastern EU countries. This study gives evidence that today's household may become trapped in particular socio-spatial settings which further give rise to energy poverty problem.

It is not an easy task to measure the energy poverty. Spreng and Pachauri [18] name two general approaches: the first one is based on estimation of basic energy needs of a household, and the second one is based on measurement in relation to access to different energy sources. In the remainder of their work, they propose an approach that combines the elements of energy access and energy consumption, and tried to explain how this concept is related to well-being of households. Nussbaumer *et al.* [22] develped a composite index to measure energy poverty, named the multi-dimensional energy poverty index. This is based on the deprivation of access to modern energy services, and tries to capture both the incidence and intensity of energy poverty.

The negative effects of energy poverty on human well-being emerge as concerns of health, education, security, income, labor productivity and social inclusion. These are well documented in the energy poverty literature [3], [18], [23], [24]. Nevertheless, its harmful environmental impacts are not that much attended. It was Sovacool [25] who highlighted issues such as deforestation, undesirable changes in land use patterns, and rise in emission of the greenhouse gases. In the near future in addition to the current manuscript, we expect more studies that consider alternative views to the energy poverty problem within the concept of locally sourced renewable/clean energy.

In this paper it was possible to concentrate on energy poverty with above viewpoint through a CPSS framework. A CPSS is a highly complex system including a physical system, a related social system that involve humans using that physical system, and a cyber-system connecting these two systems. The reason to existence of a CPSS is to serve human needs and improve quality of life. In a CPSS, humans are not only users of the system, but also become essential data providers to enhance its performance and usefulness. CPSS thinking leads to practical applications such as smart homes [26], intelligent transportation systems [27], social networking [28], and urban sensing [29].

Designing complex systems such as the CPSS is complicated itself. Predominantly, there are three approaches to design such systems including layer-based design [30], component-based design [31], and meta-model-based design [32]. In a relevant paper to our work, Zhang *et al.* [33] designed a CPSS for distributed energy management in micro-grid context where energy producer and consumer decisions are diversified according to a general-sum game.

Control and management problems arising in CPSS call for a diverse list of supporting technologies and approaches including but not limited to: cloud computing [34], tensor computation [35], linguistic dynamic systems and computing with words [36], [37], and parallel learning [33].

In this study DLT is tagged to the CPSS to work on-chain and off-chain conventions. DLT is a cyber-consensus and digital track recording mechanism that is used to enable secure transactions between the nodes of a network under a trustless environment. When digital transactions between the members of the network are stored through a central authority, the resulting system is open to one-point of failure and also to pernicious attacks [38]. On the contrary, DLT data repository, i.e. the *ledger*, is *distributed*, and hence *decentralized*.

For our purposes, besides serving as a secure apparatus for transactions, a trustable means to money transfer between parties, and a technological framework to utilizing smart metering devices, we particularly resort to the DLT in order to allow *smart contracting* at the local market level. Smart contracts are digital contracts generated by computer codes running according to certain rules and the terms of the agreement between transaction parties. They can be dynamically executed when conditions between members of a network are settled, and allow for almost-real-time operations [39]. This feature of the DLT in particular provide a large spectrum of potential application areas from generation to the consumer edges.

According to a survey among decision-makers in German energy markets conducted by the German Energy Agency [40], DLT both improves efficiency of an inherent energy system and further promotes new DLT-based energy use cases, such as the case we detail in this paper. In a report by Livingston *et al.* [41] following energy use cases are predicted to benefit from recent advancements in DLT and blockchain: P2P energy trading, grid management and system operation, financing renewable energy development, management of renewable energy certificates, and electric mobility and electric vehicle charging.

A thorough summary of the literature review is provided at Appendix A for the interested reader.

III. ARCHITECTURE AND MAIN PROCESSES OF DONATION SHARING

In this section we describe the architecture and main processes of donation sharing under smart energy CPSS. Through analysis of this use case we shall discuss how donation sharing may be facilitated in a local P2P energy market with using capabilities provided by the contemporary DLT. To this end, we first introduce the local market structure, roles of market participants and its energy trading system. Subsequently, we discuss the main processes to facilitate donation sharing and necessary interaction among layers of the smart energy CPSS in order to work through such processes.

A. LOCAL MARKET STRUCTURE AND ROLES

The local energy market we consider is a community composed of prosumers and consumers who trade energy on a P2P basis over a community micro-grid. The *prosumers* in this community are those participants of the market with installed photovoltaic (PV) capacity, and hence with self-production capability. The *consumers* do not have such capability and are willing to procure their requirements from an energy pool that is shared with the former. Energy trading and transmission are facilitated by a local market *aggregator* which plays a coordinating role in the local trade. These participants utilize smart devices and communicate through a DLT-based energy trading framework which enables transactions, dynamic smart contracting and monetary flow as illustrated in Figure 2. Physical energy flow between participants of the market is routed from a *shared energy pool* by the aggregator, hence energy trading over this framework is referred sometimes as the *routed P2P energy trading*.

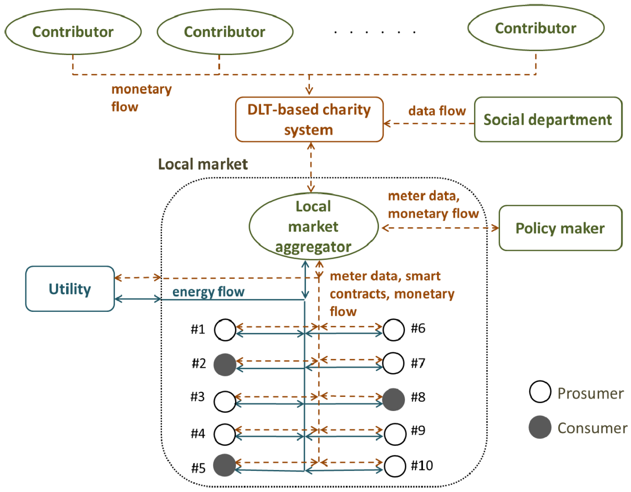

FIGURE 2. Local market and DLT-based charity system.

The *utility* is basically a utility provider company which engages in a bi-directional energy flow with the aggregator. Thus, the energy trade between local market and utility is also facilitated by the aggregator. In this paper, we do not allow energy storage while the local market functions through successive time periods. Hence, apart from the local interaction between the prosumers and consumers in the market, if there is further energy surplus in the system during each time period, it is cleared by coaction with the utility grid.

The *contributors* are individual donators to the charity, who are active online social collaborators for a common good. The *social department* is a government institution that operates at social welfare layer of the smart energy CPSS. It cooperates with the charity and provides data about potential donation recipients. The *policy maker* is an energy policy and regulatory layer public player that continuously tracks the local market, and distributes incentive to local energy producers in accordance with government policies. The *DLT-based charity system* is organized by employing contemporary DLT, and it collects donations from the contributors and route this endowment to local market in accordance with data received from the social department. It both tracks the local market and shares donation through the DLT framework, according to the market conditions.

It is worthwhile to note that, as donation recipients are financially disadvantaged participants of the market by nature, in this manuscript, we assume that they are essentially consumers. This is because, in our view, investing in PV installed capacity by such participants is unlikely. Hence, we proceed with this assumption in the remainder of this study.

B. DONATION SHARING PROCESSES

CPSS design is challenging as it contains complex interactions through boundaries of various cyber, physical and social sub-systems. We adopt a *layer-based* design for smart energy CPSS in order to better explain multi-layer interactions within the framework presented. Physical components of the CPSS represent power system related facilities of the local micro-grid under study.

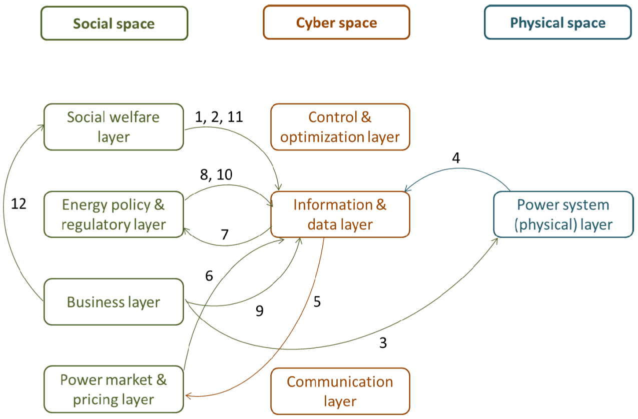

FIGURE 3. Interactions among the layers of smart energy CPSS.

An overview of necessary interactions between layers of the energy CPSS is provided in Figure 3. In order to detail processes to facilitate donation sharing in this setting, assume a *planning horizon* that is composed of individual *time periods* where local market is functioning. Then the main processes of donation sharing are designed as follows.

i. At the beginning of the planning horizon.

Process (1). (On-chain) Contributor citizens donate money to the DLT-based charity system in order to cover residential energy requirements of the donation recipients. Each contributor subscribes to the DLT network. Public-permissionless blockchain platforms, such as the *Ethereum*, are highly compatible systems for this process.

Process (2). (On-chain) DLT-based charity system must be informed on which citizen should receive donation, hence Social Department sends information on donation recipients, with keeping their personal identity anonymous, to the charity system through DLT network.

ii. At each time period.

Process (3). (Off-chain) Local market aggregator facilitates energy routing to cover energy requirements in the market.

Process (4). (On-chain) Using smart metering devices, energy generation and consumption information, hereafter denoted as EGCI, of market participants is sent to DLT network.

Process (5). (On-chain) EGCI is retrieved by local market mechanism.

Process (6). (Off-chain) Based on EGCI, local market mechanism determines a market price. *(On-chain)* Market price information is forwarded to DLT network.

Process (7). (On-chain) Policy Maker tracks EGCI through DLT network.

Process (8). (On-chain) Optionally, Policy Maker may consider distributing incentive to net energy producers in the local market, for which, there exist hybrid feed-in/flexible-access policy instruments [42] available. If it chooses to do so, based on the respective EGCI, incentive information is forwarded to DLT network.

Process (9). (Off-chain) Based on EGCI, market pricing, and optional incentive information, an economic model calculates costs and revenues of market participants. *(On-chain)* Cost and revenue information is forwarded to DLT network.

iii. At the end of the planning horizon.

Process (10). (On-chain) Optionally, Policy Maker distributes incentive through DLT network.

Process (11). (On-chain) DLT-based charity system shares donation to cover cost accumulation in the accounts of donation recipients.

Result (12). Social welfare benefits are realized.

IV. DONATION SHARING MECHANISMS

In this section, we introduce two donation sharing mechanisms specially designed for realizing the donation sharing use case under smart energy CPSS. The first mechanism is named the *external donation sharing* (EDS). In this method, donation is provided by the charity system directly to cover the energy procurement costs of donation recipients in the local market that are accumulated through the planning horizon. To track the encumbrance of donation to charity account, we analyze market pricing and relevant procurement cost distribution to consumers in the local market through this first discussion. Subsequently, we introduce another donation sharing mechanism, named the *internal donation sharing* (IDS), where energy requirements of the donation recipients are supplied within the local market and associated procurement cost is distributed to volunteering market participant accounts. As this cost is reflected to both consumers and prosumers, we also analyze revenue generation of prosumers in market through this latter discussion. Hence, in addition to providing two novel mechanisms to donation sharing, this section also establishes local market parameters and the economic model that are essential to realizing the processes introduced in the preceding section.

A. EXTERNAL DONATION SHARING (EDS)

In EDS, a record tracking the total energy procurement cost of the donation recipients is kept until the end of a prescribed time period. That record then cleared in the favor of the recipients by the charity through a transaction with the aggregator. To facilitate this, we first describe market pricing and cost distribution in the local market. Before introducing notations, we note that a thorough nomenclature is provided in Appendix B at the end of this paper.

Let t be an index for time periods where the local market is functioning and i be another index for local market participants. At each time period t, the participants are separated into a set of net energy *consumers* denoted by $NC(t)$, and a set of net energy *producers* denoted by $NP(t)$. We let the *amount of energy generated* and the *amount of energy demanded* by a participant i at t be g_{it} and d_{it}, respectively. We further let s_{it} be the *surplus energy* of participant i at t after satisfaction of its own demand, where $s_{it} = g_{it} - d_{it}$ if $g_{it} > d_{it}$ and $s_{it} = 0$ otherwise. Similarly, we let r_{it} be the *net energy requirement* of participant i at t after using its self-energy generation if available, where $r_{it} = d_{it} - g_{it}$ if $d_{it} > g_{it}$ and $r_{it} = 0$ otherwise. It should be apparent to the reader that, a prosumer may not be a net contributor to local energy surplus for every time period, due to possible self energy requirement that is greater than its energy generation. Hence, for some time periods, a prosumer may behave as a net consumer in the market.

Constructing a sensible ground to market pricing requires assessing the capability of market-level surplus energy to satisfy the market-level energy requirement. To measure this, we resort to a parameter due to [43], which is defined as the ratio of total energy surplus to the total energy requirement in the local market, and referred to as the *supply-demand ratio*. We denote supply-demand ratio at time period t with R_t which is given by:

$$R_t = \frac{\sum\limits_{i \in NP(t)} s_{it}}{\sum\limits_{i \in NC(t)} r_{it}}. \tag{1}$$

As the value of this ratio changes at each time period, market price will change according to the surplus and requirement composition in the market, yet have to be delimited between reasonable rates. Therefore, we let p_f be the *feed-in tariff* and impose it as a lower limit, whereas we let p_u be the *utility price* and define it as an upper limit to the market price.

When $R_t = 0$, there is no energy surplus in the local market at t because $s_{it} = 0$ for all participants. Hence, energy requirements must be bought from utility at the utility price, which is decidedly the market price at this period. We let p_t be the *market price* and c_{it} be the *energy procurement cost* of a net consumer i at time period t. Then we obtain $p_t = p_u$, and therefore:

$$c_{it} = r_{it} \cdot p_t = r_{it} \cdot p_u. \tag{2}$$

When $0 < R_t < 1$, the total energy surplus in the local market can satisfy the total requirement partially. If the surplus is small, R_t is close to 0 and the market price is close to the utility price. On the other hand, if the surplus is considerable, yet below the total requirement, R_t is close to 1 and the market price is close to the feed-in tariff. To emulate this mechanism for determining the market price, we use a convex combination of feed-in tariff and utility price with using the supply-demand ratio as a coefficient. Thus for $0 < R_t < 1$, we obtain the market price at time period t as follows:

$$p_t = R_t \cdot p_f + (1 - R_t) \cdot p_u. \tag{3}$$

We note for the case $0 < R_t < 1$ that, the proportion of the total requirement that cannot be supplied from the market must be bought from utility, because the total energy surplus in the market satisfy the total requirement in a part. Hence, the procurement costs c_{it} must be distributed over a total procurement cost for all net consumers since energy routed from the sharing pool comes from two sources with distinct prices. This cost distribution is applied as follows.

Distribution of individual procurement costs. We define c_t as the *total energy procurement cost* of net consumers of the market at time period t, for which we have:

$$c_t = \left(\sum_{i \in NP(t)} s_{it} \right) \cdot p_t + \left(\sum_{i \in NC(t)} r_{it} - \sum_{i \in NP(t)} s_{it} \right) \cdot p_u. \tag{4}$$

In this totality, the proportion of the total energy requirement that is acquired from available surplus in the local market is:

$$\sum_{i \in NP(t)} s_{it}, \tag{5}$$

and this leaves the remaining proportion that is supplied from the utility as:

$$\sum_{i \in NC(t)} r_{it} - \sum_{i \in NP(t)} s_{it}. \tag{6}$$

The first part given by Equation (5) is bought from local market at the market price. Then, the cost associated with this local trade amounts to:

$$\left(\sum_{i \in NP(t)} s_{it} \right) \cdot p_t. \tag{7}$$

The second part given by Equation (6) is bought from the utility at the utility price. Thus, cost associated with this procurement amounts to

$$\left(\sum_{i \in NC(t)} r_{it} - \sum_{i \in NP(t)} s_{it} \right) \cdot p_u. \tag{8}$$

As clarified above, the energy procured by net consumers is routed from the energy sharing pool and originate in two sources with different prices. Then, the total energy procurement cost will be apportioned among such net consumers according to their *share* in the total requirement to obtain individual procurement costs of net consumers. This can be accomplished as follows:

$$\begin{aligned} c_{it} = \frac{r_{it}}{\sum_{i \in NC(t)} r_{it}} \cdot \Bigg(\left(\sum_{i \in NP(t)} s_{it} \right) \cdot p_t \\ + \left(\sum_{i \in NC(t)} r_{it} - \sum_{i \in NP(t)} s_{it} \right) \cdot p_u \Bigg), \end{aligned} \tag{9}$$

where the term

$$\frac{r_{it}}{\sum_{i \in NC(t)} r_{it}} \tag{10}$$

is the share of an individual net consumer i in total energy requirement.

As we noted that energy routed from the sharing pool originate in two sources with different prices, naturally, net consumers' unit cost for energy procurement at t is different from effective market price. The individual cost representation (9) gives invaluable information about this unit cost. Suppose we move the outside denominator $\sum_{i \in NC(t)} r_{it}$ in equation (9) to inside, to obtain:

$$\begin{aligned} c_{it} = r_{it} \cdot \Bigg(& \left(\frac{\sum_{i \in NP(t)} s_{it}}{\sum_{i \in NC(t)} r_{it}} \right) \cdot p_t \\ & + \left(\frac{\sum_{i \in NC(t)} r_{it}}{\sum_{i \in NC(t)} r_{it}} - \frac{\sum_{i \in NP(t)} s_{it}}{\sum_{i \in NC(t)} r_{it}} \right) \cdot p_u \Bigg) \end{aligned} \tag{11}$$

which, according to the definition of supply-demand ratio (1), is equal to:

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

We further let u_t be the *unit procurement cost* at time period t which, by definition, is equal to:

$$c_{it} = r_{it} \cdot u_t \,. \tag{13}$$

Then, to sum up, from (12)-(13) we conclude that unit price of procurement is a convex combination of the market price and utility price with the supply-demand ratio as a coefficient. This result establishes the mathematical description of the unit procurement cost when $0 < R_t < 1$.

Finally, when $R_t \geq 1$, there is excess energy surplus in the local market. Thus, remaining energy after satisfying all net requirements is sold to utility at feed-in tariff, which this time, is decidedly the market price at this period. Accordingly, we obtain $p_t = p_f$ and:

$$c_{it} = r_{it} \cdot p_t = r_{it} \cdot p_f \,. \tag{14}$$

Therefore, in general, the procurement cost of a net consumer i at time period t is given by $c_{it} = r_{it} \cdot u_t$ where:

$$u_t = \begin{cases} p_u, & \text{if } R_t = 0, \\ R_t \cdot p_t + (1 - R_t) \cdot p_u, & \text{if } 0 < R_t < 1, \\ p_f, & \text{if } R_t \geq 1. \end{cases} \tag{15}$$

We now have enough information to keep track of cost accumulation in distinct accounts for each net consumer, including the donation recipients. Similarly, total costs to charity can be accumulated in a charity account. Then, considering such an account, let $b^c_{it^*}$ be the *account balance* of a consumer i at a given time period t^*. This may be constructed as:

$$b^c_{it^*} = -\sum_{t=0}^{t^*} c_{it} \,. \tag{16}$$

Moreover, let the set of *donation recipients* be D, then the *charity account balance* b_{t^*} to be cleared at t^* is given by:

$$b_{t^*} = -\sum_{t=0}^{t^*} \sum_{i \in D} c_{it} \,. \tag{17}$$

B. INTERNAL DONATION SHARING (IDS)

In IDS, energy requirements of the donation recipients are supplied within the local market instead of resorting to charity account. The participation to donation sharing is completely on a voluntary basis, hence a market participant is not necessarily a participant to the donation sharing mechanism. To differentiate between these two, we use the term *volunteering* for the latter. Donation sharing processes described in Section 3 operate as intended, except for the fact that volunteering participants subscribe to DLT-based charity system without donating money in advance, and the charity system does not clear donation recipient accounts at the end of planning horizon. Instead, the cost associated with the total energy requirements of donation recipients is apportioned equivalently among the volunteering participant accounts at each time period.

Suppose n market participants step forward to volunteer in IDS. Then at a time period t, each one concede paying for the energy requirement proportion:

$$\frac{\sum_{i \in D} r_{it}}{n} \tag{18}$$

at the effective market price. For volunteering consumers associated cost is appended to their individual procurement cost, whereas for volunteering prosumers it is subtracted from their individual revenue.

When $R_t = 0$ and there is no energy surplus in the local market at t, donation will bring an additional cost of $(\sum_{i \in D} r_{it}/n) \cdot p_u$ to each volunteering participant. Hence, for volunteering consumers we have:

$$c_{it} = \left(r_{it} + \frac{\sum_{i \in D} r_{it}}{n} \right) \cdot p_u. \tag{19}$$

Let y_{it} be the *revenue*, i.e. the yield, of a prosumer at time t. Similarly, since for all prosumers we have $s_{it} = 0$ and none of them is a net producer when $R_t = 0$, the revenue for a volunteering prosumer is given by:

$$y_{it} = -\left(r_{it} + \frac{\sum_{i \in D} r_{it}}{n} \right) \cdot p_u. \tag{20}$$

When $0 < R_t < 1$, where the total energy surplus in the local market partially satisfies the total requirement, volunteering consumers incur a cost of

$$c_{it} = \left(r_{it} + \frac{\sum_{i \in D} r_{it}}{n} \right) \cdot u_t, \tag{21}$$

where the unit cost u_t is calculated according to principles introduced in the preceding section.

When it comes to prosumers, recall that they are not necessarily a net producer at every time period. In general, if a prosumer is a net producer at t, it will make a revenue of $s_{it} \cdot p_t$, otherwise it is a net consumer and charged $r_{it} \cdot u_t$. Thus when $0 < R_t < 1$, for a volunteering prosumer we have:

$$y_{it} = \begin{cases} s_{it} \cdot p_t - \frac{\sum_{i \in D} r_{it}}{n} \cdot u_t, & \text{if } i \in NP(t), \\ -\left(r_{it} + \frac{\sum_{i \in D} r_{it}}{n}\right) \cdot u_t, & \text{if } i \in NC(t). \end{cases} \tag{22}$$

On the other hand, when $R_t \geq 1$ with ample energy surplus in the local market, for volunteering consumers procurement costs are given by:

$$c_{it} = \left(r_{it} + \frac{\sum_{i \in D} r_{it}}{n}\right) \cdot p_f, \tag{23}$$

whereas for volunteering prosumers corresponding revenues may be calculated with using:

$$y_{it} = \begin{cases} \left(s_{it} - \frac{\sum_{i \in D} r_{it}}{n}\right) \cdot p_f, & \text{if } i \in NP(t), \\ -\left(r_{it} + \frac{\sum_{i \in D} r_{it}}{n}\right) \cdot p_f, & \text{if } i \in NC(t). \end{cases} \tag{24}$$

Similarly to costs for consumers, prosumers' revenues may be accumulated in individual accounts. To do so, we let b^p_{it*} be the *account balance* of a prosumer i at a given time period $t*$, which is then constructed as:

$$b^p_{it*} = \sum_{t=0}^{t*} y_{it}. \tag{25}$$

With this last extraction of a prosumer's balance we come to an end of our discussion with the IDS and EDS mechanisms. Nevertheless, there exists one fair extension that is not our main focus in this paper, yet it has to be discussed before presenting our illustrations with these schemes. Through our analysis we assumed that the donation recipients are honest participants of the system and do not misuse the donation sharing opportunity. That is, the donation recipients are not using free energy significantly more than their ordinary demand. Thus, we assumed such consumption is more or less the same as their past track record. Otherwise, to alleviate such remedy there may be a reasonable limit on the amount of energy shared with each recipient. If the consumption is within such limit, donation sharing will continue as we have discussed in previous sections. If the consumption is significantly above such limit, the donation recipient may be informed and billed for the excess amount.

Another issue is that a subset of volunteering participants may not prefer to continue donation sharing after a certain amount of energy donated, for the sake of their own bills. Therefore, they may prefer to adopt a pre-defined limit on the maximum amount of energy donated to the recipients. In Appendix C we clarified such a scenario and show how the cost and revenue parameters introduced in this section may be re-distributed in that case.

V. ILLUSTRATION OF DONATION SHARING EFFECT

In this section we illustrate how donation sharing mechanisms effect charity and participant accounts by resorting to a mix of six base scenarios. First, we clarify how we organized the data and experiments, then we derive base scenarios which will be used later in a combined manner, for our purposes in the following sections. Next, we illustrate EDS impinging upon the charity account balance with tracking the cost accumulation of a representative donation recipient consumer through time periods. Subsequently, we illustrate IDS effect on account balances of volunteering participants.

A. PLANNING OF EXPERIMENTS AND SCENARIOS

To highlight the essences of local market mechanism and donation sharing, we created a representative local market as a testbed for practicing experiments with scenarios. The local market we designed is composed of 10 participants and the local market aggregator, 7 of which are prosumers with PV installed capacity and remaining 3 are regular consumers as shown in Figure 2.

For assigning realistic energy generation and consumption profiles to all participants, we used CREST demand modeling tool due to [44], [45]. CREST is a stochastic model to simulate thermal and electricity demand intended for domestic users. We particularly find this model useful for our analysis with the local P2P network because of its capability of producing appropriate demand pattern diversity. The model is primarily based on extensive survey data and produces realistic demand patterns taking daily occupancy and activities of households into account. It incorporates authentic representations of electricity demand, as well as electricity generation and hot water consumption. Moreover, the model considers usage patterns of home appliances due to sensitivities in household occupancy and its timing. For these reasons, we consider this model as a perfect tool for our purposes to simulate the energy profile for the local market testbed under study. Another important feature of CREST we find desirable is that it is a validated model through a series of credible scientific work [44]–[46]. Lastly, we were able to produce series of high-resolution data with this particular model.

We generated a single day sample energy profile including all participants, with using CREST in one-minute resolution. Then, we aggregated this data to obtain 15-minute time intervals. Generating sensible market conditions through these intervals requires imposing realistic market price limits, therefore we used German market feed-in tariff and utility price due to [42]. According to this convention, we set the feed-in tariff p_f to 12,31 €c/kWh, and the utility price p_u to 28,69 €c/kWh.

For illustration purposes, we differentiate between operation of a local market mechanism and a donation sharing mechanism. Both require the DLT framework to be realized, yet not necessarily each other to be operative. They can be in effect individually, as well as collectively as we studied in the preceding sections, by using the same DLT structure. We considered six base scenarios, combinations of which were employed at each experiment with the deterministic data introduced above. The base scenarios are constructed as follows.

Scenario (1). (No Market) The local market is not formed and participants engage in individual transactions with the utility at feed-in tariff and utility price.

Scenario (2). (Local Market) The local market mechanism is in effect and participants engage in P2P energy trading at the market price.

Scenario (a). (External) Donation sharing is provided externally by the DLT-based charity system.

Scenario (b). (Internal) Donation sharing is provided internally by volunteering participants and charity account is not in effect.

In order to present the effect of IDS, we select one prosumer and a consumer who essentially is not a donation recipient, and further call these participants the *selected group* hereafter. Under this definition, two remaining base scenarios are given as follows.

Scenario (i). (Volunteer) Selected group volunteer participating in IDS.

Scenario (ii). (Decline) Selected group decline participating in IDS.

The experiment is conducted on typical number crunching software and composed of a group of calculations, i.e. a *run*, for each relevant combination of the base scenarios considered. For each run, we experimented with the same deterministic sample energy profile on the local community we designed, by operating the market for a complete 24-hour period. Runs are initiated by midnight covering 96 time periods, i.e. 15-minute resolution for 24 hours, until the midnight next day to generate and report market parameters we introduced in preceding sections.

B. EDS EFFECT: ILLUSTRATION OF THE CHARITY ACCOUNT

In order to show daily cost accumulation in charity account when EDS is operative, we combined base Scenarios (1) and (2) with Scenario (a) to obtain Scenarios (1a) and (2a). Hence in this section we study:

Scenario (1a). Local market mechanism is not in effect, yet EDS is in effect.

Scenario (2a). Both local market mechanism and EDS are in effect.

We run the local market for above scenarios supposing that Consumer 8 is the donation recipient. Procurement costs for Consumer 8 are calculated according to equations (7-8) and illustrated in €c at Figure 4. From midnight to early morning there is a low-cost consumption pattern originating from mild energy requirement by Consumer 8 due to household inactivity. Since there is no PV energy generation in the market until 05:15 AM, market price equals the utility price and the procurement costs for Scenarios (1a) and (2a) go in line with each other. By 5:15 AM, a period of active PV energy generation starts, as such, a differentiation in procurement costs sets in. There is an exceptional morning rush hour between 07:45 AM - 08:45 AM where procurement costs for Scenarios (1a) and (2a) are again identical. After this period there is available energy surplus in the market, where due to the market mechanism, procurement cost for Scenario (2a) is significantly lower than that for Scenario (1a). This productive PV energy generation period lasts until 17:45 PM. Between 16:45 PM - 17:45 PM procurement costs are almost identical due to very low energy surplus when compared to net requirement in the market. This effect may be recognized better by resorting to supply-demand ratios according to Equation (1), which come out as 0,0628; 0,1662; 0,0521; and 0,0728 for this one-hour period. 16:00 PM - 22:00 PM shows a period of high consumption marked with double peaks, one observed at 17:15 PM and the other at 18:45 PM. Equivalence of procurement costs after 17:45 PM again shows that there is no energy surplus in the market and the requirement is supplied at utility price. After 22:00 PM there is another low consumption period with delicate cost pattern until midnight.

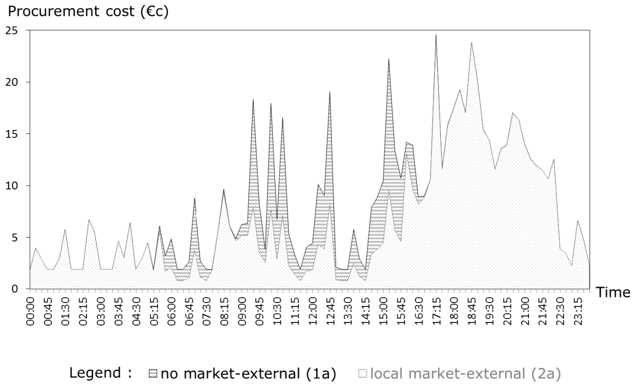

FIGURE 4. Procurement costs of the donation recipient.

Suppose the DLT-based charity system clears the cost accumulation of donation recipients at the end of each day. When tagged to a charity account, the daily energy procurement of Consumer 8 leads to account balance calculated by using Equation (10) and illustrated at Figure 5. It is clear that the cost accumulation is lower when local market mechanism is in effect. Charity account piled up a balance of €–7,72 for Scenario (1a) at the end of the day, whereas the balance points out a mere €–6,21 for Scenario (2a) considering this daily sample energy profile.

Among other things this really shows that establishment of a proper local market mechanism not only reduces energy procurement costs for consumers, but also points out that it cuts down the financial burden on the charity system. Hence, it increases charity's flexibility to route scarce funds to other innumerous relief efforts. We strongly believe that it is a nice representation of a humble local market initiative positively affecting a common good in different dimensions.

C. IDS EFFECT: ILLUSTRATION OF PARTICIPANT ACCOUNTS

To illustrate the effect on participant accounts when IDS is operative, first we recall the selected group as representative participants, then incorporate base Scenarios (1)-(2) and

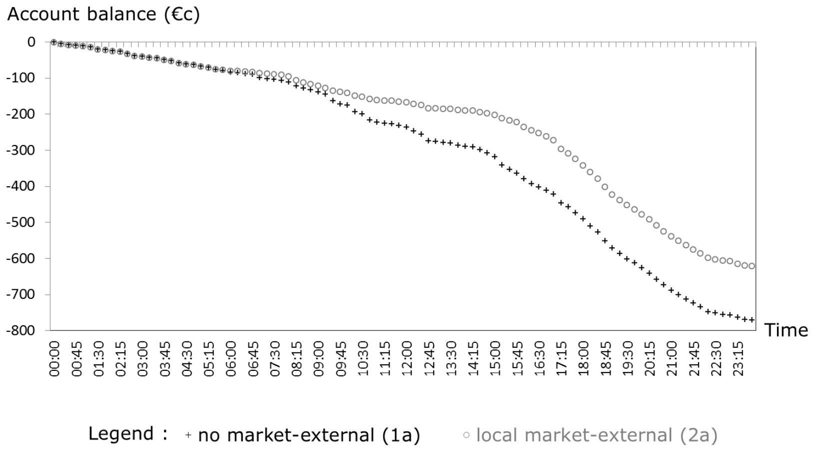

FIGURE 5. Charity account balance.

(i)-(ii) with Scenario (b) to obtain Scenarios (1bi), (2bi), (1bii), and (2bii). Hence we consider:

Scenario (1bi). Local market mechanism is not in effect, on the other hand IDS is in effect and selected group actively participate to it.

Scenario (2bi). Both local market mechanism and IDS are in effect and selected group actively participate to it.

Scenario (1bii). Local market mechanism is not in effect, on the other hand IDS is in effect, however selected group does not participate to it.

Scenario (2bii). Both local market mechanism and IDS are in effect, however selected group does not participate to it.

It is useful here to further clarify Scenarios (1bii) and (2bii). These are brought up as declining scenarios where the participants deemed as members of the selected group decline to involve in donations and hence the IDS. However this does not mean IDS is not imposed at the market. It is imposed with other participants taking roles in it. We bring in Scenario (2bii) just to see the effect when a group of consumers and producers continue without such donation sharing roles and try to take the advantage of local market conditions. Then Scenario (1bii) is utilized to consider a case where participants do not engage in energy trading among themselves but the utility. This ensures a viable comparison with other scenarios where such participants can not benefit from local market and engage with utility over the feed-in tariff and utility prices.

For this experiment again suppose that Consumer 8 is the donation recipient and there are 7 volunteering participants to IDS. Moreover, we assign Consumer 2 and Prosumer 3 to the selected group, hence if they also volunteer to take part, procurement costs of Consumer 8 will be covered by $n = 9$ market participants equally. Thus, in this case all participants except the donation recipient actively contribute to donation sharing. We run the market with above scenarios to obtain effects of IDS to selected group accounts. To this end, procurement costs of Consumer 2 are illustrated in Figure 6. In case Consumer 2 participates to IDS, at each time period, it pays one-nineth of the procurement cost of Consumer 8. Hence, there is always a residual between pointers of the costs for Scenario groups (*bi) and (*bii). When energy consumption of Consumer 8 is low this residual is small, e.g. midnight hours; and when the consumption is high the residual is large, e.g. night peak hours. Costs for Scenarios (1bi)-(2bi) and (1bii)-(2bii) coincide in respective groups to follow a single pattern marking the periods where market price equals either p_f of p_u. Otherwise, costs for four scenarios differentiate due to market price effect on the unit procurement cost. It is evident that participation to IDS is a mediocre constituent to procurement costs of Consumer 2, rather the main determinant is the existence of a proper local market mechanism. For example at 10:45 AM, the cost for Scenario (2bi) is significantly lower than that for Scenario (1bii), which means Consumer 2 incurs lower cost in a local market mechanism, though it participates to donation sharing; whereas the procurement cost is higher when the market is not present even if participation to donation sharing is declined. This really shows that the local market mechanism provides an effective cost margin to its participants, which may serve as a financial flexibility to participate in IDS.

We also generated the account balance of Consumer 2 for these scenarios, which is illustrated in Figure 7. The above effect best externalized in this figure as Consumer 2 ends up with an account balance of €–5,45 for Scenario (2bi), whereas the end-day balance for Scenario (1bii) shows an accumulation of €–5,90 for this sample daily energy profile. This demonstrates that in the presence of a local market mechanism it is possible to participate donation sharing and still incur a lower procurement cost, than that arouse where donation sharing is declined but the local market mechanism is not in effect. On the other hand, when participation to donation sharing is declined under local market mechanism the end-day account balance for Scenario (2bii) was as low as €–4,76, whereas Consumer 2 completes this sample day

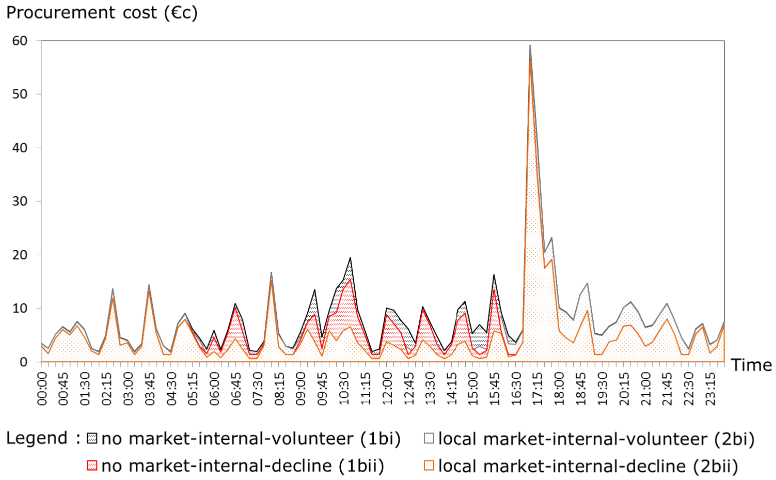

FIGURE 6. Procurement costs of Consumer 2 when $n = 9$.

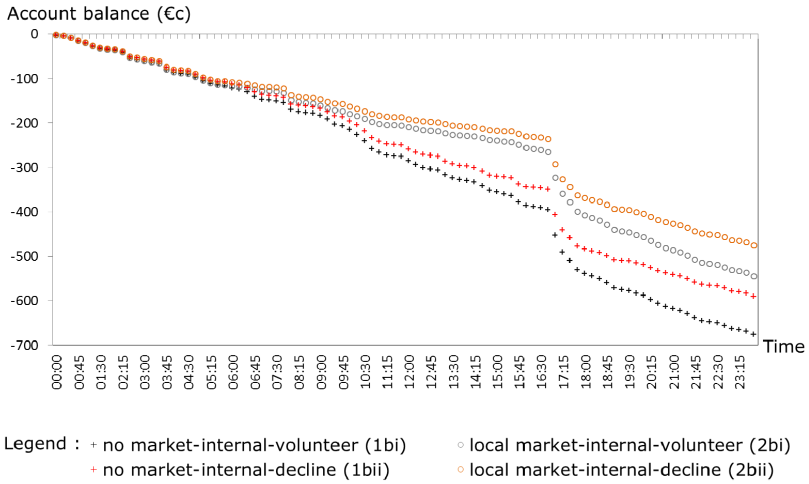

FIGURE 7. Account balance of Consumer 2 when $n = 9$.

with a balance of €–6,76 in Scenario (1bi) if it chooses to participate to donation sharing although the local market is not functioning.

Nevertheless, when participation to IDS is limited, the financial advantage provided by the existence of a local market may not be retained until the end of the day by volunteering consumers. To illustrate this, suppose now there are merely $n = 4$ participants to IDS including the selected group. We run the local market with this setup where the resultant account balance of Consumer 2 is illustrated in Figure 8. Note that, in this case cost accumulation for Scenarios (1bii) and (2bi) break-even between periods 19:30 PM and 19:45 PM. This really shows that Consumer 2, enjoying energy procurement at local market price through the day under Scenario (2bi), cease to hold this cumulative advantage versus the case for Scenario (1bii) and ends this sample day with a balance of €–6,32 by volunteering to donation sharing under local market conditions when compared to €–5,90 that marks accumulation under Scenario (1bii).

Having said that Consumer 2 is procuring energy at advantageous local market prices through the day, we believe that another tendency in this graph worth clarification here. It is the observation that the cost accumulation experiences a sharp increase, which corresponds to a sharp decrease in the series of the graph through late afternoon, and that returns to a mild decrease at evening and night time. The reason for this observation is two-fold. First, late afternoon marks the end of productive PV energy generation in the local market, hence the consumers cease to hold such price advantage and start procuring energy from utility at the utility price. Second, it marks a peak period of high energy consumption at the market as illustrated in Figure 6 before. In succeeding evening and night hours a period of mild energy consumption follows, and hence the graph series again resume to the mild decrease.

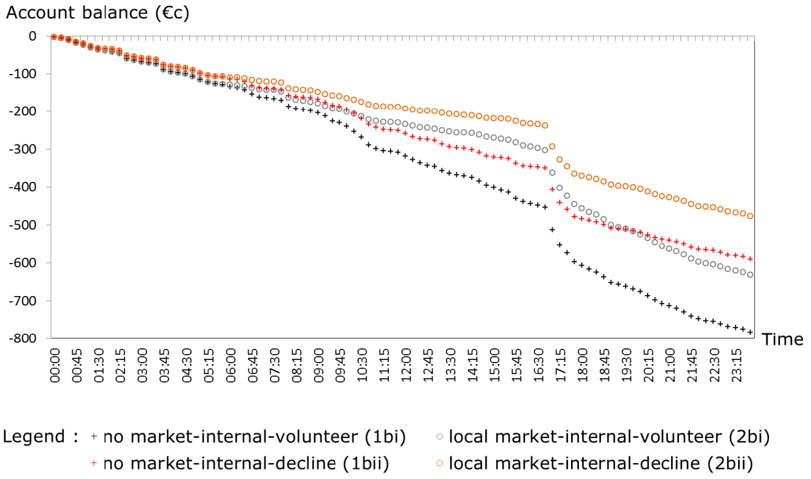

FIGURE 8. Account balance of Consumer 2 when $n = 4$.

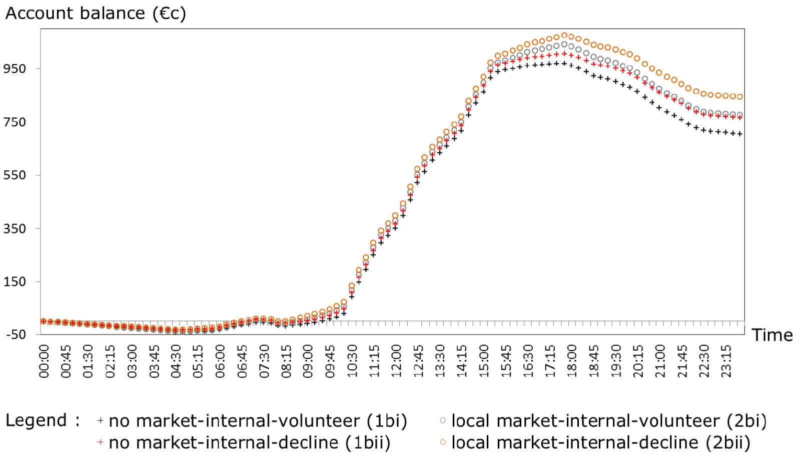

FIGURE 9. Account balance of Prosumer 3 when $n = 9$.

When it comes to Prosumer 3, the other participant in the selected group, the run with $n = 9$ participants to IDS produced the cumulative revenues for four scenarios as illustrated by the account balance given at Figure 9. Starting from midnight, it is recognizable that Prosumer 3 is not a net energy producer until 05:00 AM, rather it is a net consumer with a mild energy requirement, and hence with negative revenues, which result account balance demonstrating a mild decrease until this period. After this point, Prosumer 3 is a net contributor to energy surplus in the market, and account balance recover at a better pace until the start of the morning rush hour in the market. Between 07:45 AM and 8:15 AM there is another short period of decline in the account balance where the energy requirement of Prosumer 3 exceeds its PV generation, yet after the morning rush hour period, Prosumer 3 is a constant revenue collector until the end of a very productive PV energy generation period marked by 17:45 PM. It is also where maximum revenues are attained for all scenarios under study, since PV energy generation halts after this point and revenues restate declining. The period between 16:00 PM and 22:00 PM is characterized with high energy consumption in the local market and so for Consumer 8, the donation recipient, and this period is where notable differentiation in revenues for four scenarios occurs. The period after 22:00 PM until midnight is yet another time period with low energy requirement by Consumer 8, hence revenues of Prosumer 3 decline at a slower rate in comparison to that observed between 17:45 PM and 22:00 PM. Prosumer 3 ends this sample day with revenues €7,74 for Scenario (2bi) and €7,66 for Scenario (1bii), respectively.

In addition to Consumer 2, the first member of the selected group, it is valuable to recognize that the other member with a different role is yet again better off, this time in terms of revenues, by volunteering to IDS under the local market mechanism when compared to the case where participation to this initiative is declined given that the local market is not formed. This again shows that the existence of a proper local market mechanism provides a favorable financial margin to

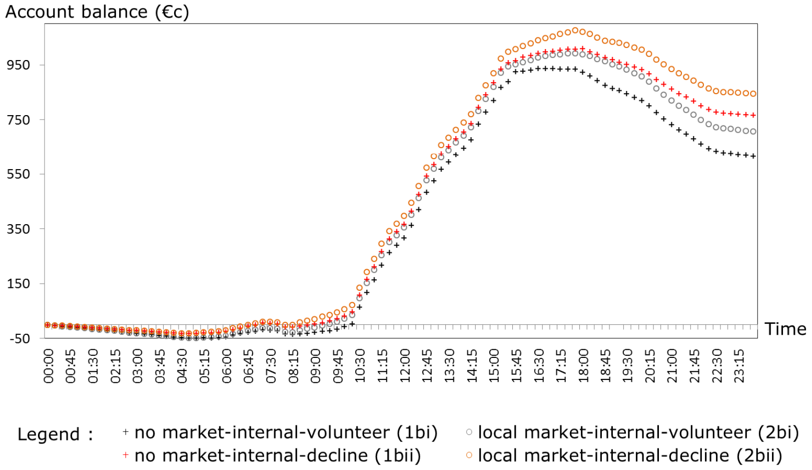

FIGURE 10. **Account balance of Prosumer 3 when $n = 4$.**

its participants where a proportion of this may be reserved for contributing to IDS. For this sample daily energy profile it is also worthwhile to note that, if Prosumer 3 declines participation to IDS under the local market mechanism, the end-day account balance for Scenario (2bii) was as high as €8,43. On the other hand, Prosumer 3 earns €7,04 in Scenario (1bi) for this sample day where it chooses to participate to IDS although the local market is not formed.

As far as additional cost associated with covering energy requirements of donation recipients is considered, participation is the key to IDS in reducing the financial burden on volunteering participant accounts. What will happen to such accounts if participation tends to reduce? To see this effect consider end-day account balance of Prosumer 3 illustrated for different participation schemes in Table 1.

TABLE 1. **Prosumer 3 end-day account balance under different participation schemes.**

Participation	Volunteering scenarios		Declining scenarios	
	1bi	2bi	1bii	2bii
$n = 9$	7,04	7,74	7,66	8,43
$n = 6$	6,52	7,33	7,66	8,43
$n = 4$	6,17	7,06	7,66	8,43

In this small experiment, participation is first reduced to $n = 6$ participants and then to $n = 4$ participants to IDS, respectively. We clearly recognize the vanishing effect on Prosumer 3 revenues under volunteering scenarios. For the declining scenarios, obviously end-day balance will not alter as Prosumer 3 declined to participate the IDS beforehand. Most importantly, as we reduce participation, it is possible that the participant(s) may cease to hold the favorable financial margin realized through local market mechanism under Scenario (2bi) after some point. Similarly to Consumer 2, it is recognizable that Prosumer 3 cease to hold such financial margin under the local market mechanism with Scenario (2bi) and accumulates revenues of €7,33 and €7,06 for the cases of limited participation to IDS, respectively. Clearly, under limited participation this participant falls behind €7,66 attainable under Scenario (1bii) for this sample daily energy profile.

Lastly, we mull over how this may effect the graph for daily revenue accumulation for a participating prosumer. To see such effect on graph we again resort to the illustrative case with $n = 4$ participants to IDS including the selected group, and show resultant account balance for Prosumer 3 in Figure 10. The graph clearly shows that revenue accumulation under scenario Scenario (1bii) surpasses that for Scenario (2bi) due to low participation to IDS.

VI. CONCLUSION, LIMITATIONS, AND FUTURE RESEARCH DIRECTIONS

When investigated under a multi-layer complex architecture, the smart energy system that accommodate P2P local energy market exhibit essential characteristics of what we call a CPSS. In typical CPSS the data acquired from sensors in a social network, i.e. the end-users, is used in a progressive manner to improve overall service level of the system to produce user benefits. Starting from this standpoint and aiming prospective social welfare benefits, we analyzed a new use case applicable under DLT capabilities and smart energy CPSS as an alternative sharing economy concept. In this concept, essential end-user information from various sources such as the social department and smart-metering devices is retrieved and donation sharing mechanisms are put forward to contend the energy poverty problem.

We believe that studying this new use case is meaningful to address two apertures in the current state-of-the-art of energy poverty as highlighted in the introduction. These are the need regarding new approaches that focus on energy affordability rather than well-studied energy access/grid expansion axis, and the need to look for promising solutions within the distributed generation/renewable energy domain. While fulfilling these grounds we also introduce a resource-pooling approach which was yet another promising direction to contest the energy poverty problem.

Other deeds of our study and evident inferences from our experiment may be summarized in four points. First, as far as its contribution to the financially-disadvantaged is considered in EDS, it is shown that the financial burden on the charity system is reduced in case of an active local market framework. Hence its financial flexibility to struggle with numerous other appeals is remarkably enhanced. Second, the valuable financial margin attainable by participating a proper local market mechanism, i.e. the cost reduction for consumers and revenue generation for prosumers in the market, can be partially utilized to contest with domestic energy poverty through IDS. Third, participation in terms of the number of participants to donation sharing is the key to successfully realize the former interpretation by allowing a gentle distribution of financial encumbrance amongst them. And finally the fourth, this use case is a practical conceptualization of an extended sharing economy apparatus inspiring new generation local energy market business models as well as policies to contest energy poverty in a coordinated manner.

Nevertheless, the above do not come without some limitations. Recall that the backbone of the local market under study at community level is essentially a micro-grid. Such systems are sometimes criticized by the proponents of the traditional energy supply chain from stability and resilience perspectives. Our aim in this paper is neither related to design considerations nor control strategies and integration of microgrids. Therefore, we set our current work apart from such controversy and do not base our analysis to any assessment in that line of research. Another limitation in this work is that we did not incorporate operating costs and energy requirements for local market aggregator and the DLT network. In reality, amortization of establishing an aggregator/DLT network framework must be taken into consideration in the long term operation of the local market. Accordingly, it may also be a good idea to deduct fixed-charge type operation costs from market participant accounts at each time period or at the end-day balances. These issues were not yet accounted in this initial system of donation sharing and introductory economic models.

On the other hand this line of research may offer promising future pathways for those studying the energy poverty problem. Different mechanisms those somehow practice resource pooling both in shared energy and monetary terms may be investigated. Moreover, new approaches those care for this problem where it is initiated, i.e. in a distributed setting, will be highly valued from clean energy and sustainability perspectives. Others may implement economical analysis to highlight potential or deficiency of running an aggregator/DLT framework at community level as an accompaniment study to our work.

APPENDICES

APPENDIX A
LITERATURE REVIEW SUMMARY

A summary of subject literature is presented in Table 2.

APPENDIX B
NOMENCLATURE

ABBREVIATIONS

CPSS : cyber-physical social system
DLT : distributed ledger technology
P2P : peer-to-peer
ECGI : energy generation and consumption information
EDS : external donation sharing
IDS : internal donation sharing

INDICES

t : index for time periods
i : index for local market participants

SETS

$NC(t)$: set of net energy consumers at time period t
$NP(t)$: set of net energy producers at time period t
D : set of donation recipients
V^- : set of volunteering participants those adopt limit l
V^+ : set of volunteering participants those ignore limit l

PARAMETERS

g_{it} : amount of energy generated by a participant i at t
d_{it} : amount of energy demanded by a participant i at t
s_{it} : surplus energy of participant i at t
r_{it} : net energy requirement of participant i at t
R_t : supply-demand ratio at t
p_f : feed in tariff
p_u : utility price
p_t : market price at t
c_{it} : energy procurement cost of a net consumer i at t
c_t : total energy procurement cost of net consumers at t
u_t : unit procurement cost at time period t
$b^c_{it^*}$: account balance of consumer i at t^*
b_{t^*} : charity account balance to be cleared at t^*
n : number of volunteering market participants
y_{it} : revenue of prosumer i at t
$b^p_{it^*}$: account balance of prosumer i at t^*
l : max. amount of energy donated by a single participant
m : number of participants those ignore l

APPENDIX C
IDS WITH LIMITS

When a subset of volunteering participants do not prefer to continue donation sharing after a certain amount of energy donated, a limit that impose such a restriction must be put in place. On the other hand, remaining participants in the volunteering group may choose not imposing such a limit. Suppose a limit l is assigned to the maximum amount of energy donated by a single participant, and let V^- and V^+ be sets of volunteering participants those adopt, and those ignore this limit, respectively. If the share of each volunteering participant in total donation is smaller than or

TABLE 2. Summary of subject literature.

Paper	Energy poverty	CPSS	DLT-Other	Feature
[1]	●			Energy services & environmental sustainability
[2]	●			Energy & transport poverty
[3]	●			Health, safety, income and productivity effects
[4]	●			Rural electrification policy
[5]	●			Energy access
[6]	●			Energy deprivation; energy & fuel poverty
[7]	●			Special examination of energy poverty in EU
[8]	●			Special examination of energy transition in Germany
[9]	●			Energy poverty policies in EU
[10]	●			Energy vulnerability
[11]	●			Energy access & rural electrification
[12]	●			Rural electrification; Empirical study
[13]	●			Energy access & rural electrification
[14]	●			Grid expansion
[15]	●			Energy poverty & affordability
[16]	●			Energy poverty & distributed generation
[17]	●			Strategic challenges to global energy system
[18]	●			Method development to measure the energy poverty
[19]	●			Socio-technical systems & energy governance
[20]	●			Energy efficiency
[21]	●			Geographic interpretation of energy poverty
[22]	●			Multi-dimensional energy poverty index
[23]	●			Energy poverty negative effects
[24]	●			Energy poverty negative effects; Indonesia case
[25]	●			Energy poverty environmental effects
[26]		●		Concept of pervasive spaces
[27]		●		Intelligent transportation application
[28]		●		Device-to-device application
[29]		●		Urban sensing
[30]		●		Layer-based design of the CPSS
[31]		●		Component-based design of the CPSS
[32]		●		Metamodel-based representation
[33]		●		CPSS for micro-grid management
[34]		●		CPSS & concept of smart cities; cloud application
[35]		●		Tensor computation & big data
[36]		●		Linguistic dynamic systems for CPSS
[37]		●		Computing with words for CPSS decision making
[38]			●	DLT & pernicious attacks
[39]			●	Blockchain & smart contracting
[40]			●	Blockchain & the energy system; Survey
[41]			●	Blockchain & the energy system
[42]			●	DLT & P2P energy trading; Incentive policies
[43]			●	Demand response; Supply-demand ratio based modelling
[44]			●	Energy demand modelling; Stochastics; Simulation
[45]			●	Energy demand modelling; Stochastics; Simulation
[46]			●	Energy demand & distribution network modelling

equal to this limit, i.e.

$$\frac{\sum_{i\in D} r_{it}}{n} \leq l, \tag{26}$$

donation sharing resume as discussed in Section 4.B. Else if the share of each volunteering participant in total donation exceeds this limit, i.e.

$$\frac{\sum_{i\in D} r_{it}}{n} > l, \tag{27}$$

excess demand must be redistributed among participants that ignore the limit. Suppose there are m such participants, then the excess demand to be distributed to these participants is:

$$\sum_{i\in D} r_{it} - nl \tag{28}$$

hence, each participant ignoring the limit is billed an additional amount:

$$\frac{1}{m} \cdot \left(\sum_{i\in D} r_{it} - nl \right). \tag{29}$$

Then cost and revenue parameters diverge from the unlimited case given by Equations (19-24) in Section 4.B., but in a similar fashion in relation to R_t at each time period. For example, for the case with $0 < R_t < 1$ we have:

$$c_{it} = \begin{cases} (r_{it} + l) \cdot u_t, & \text{if } i \in V^-, \\ \left(r_{it} + l + \frac{\sum_{i \in D} r_{it} - nl}{m} \right) \cdot u_t, & \text{if } i \in V^+, \end{cases} \tag{30}$$

and,

$$y_{it} = \begin{cases} s_{it} \cdot p_t - l \cdot u_t, & \text{if } i \in NP(t), V^- \\ -(r_{it} + l) \cdot u_t, & \text{if } i \in NC(t), V^- \\ s_{it} \cdot p_t - \left(l + \frac{\sum_{i \in D} r_{it} - nl}{m} \right) \cdot u_t, & \text{if } i \in NP(t), V^+ \\ -\left(r_{it} + l + \frac{\sum_{i \in D} r_{it} - nl}{m} \right) \cdot u_t, & \text{if } i \in NC(t), V^+. \end{cases} \tag{31}$$

Parameters for other two cases with $R_t = 0$ and $R_t \geq 1$ is very similar to above extraction and trivial to the reader.

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