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SURVEY

Survey and Analysis of Local Energy Markets Based on Distributed Ledger Technologies

GODWIN C. OKWUIBE[1,2], **(Member, IEEE), THOMAS BRENNER**[2], **PETER TZSCHEUTSCHLER**[1], **AND THOMAS HAMACHER**[1]

[1]School of Engineering and Design, Technical University of Munich, 80333 Munich, Germany
[2]OLI Systems GmbH, 67376 Harthausen, Germany

Corresponding author: Godwin C. Okwuibe (godwin.okwuibe@tum.de)

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ABSTRACT Local energy markets (LEMs) provide opportunity to handle the challenges arising from the lower grid level while using the traditional top-down approach to manage distributed generated renewable energy resources. Blockchain-based local energy markets (LEMs) have been introduced in recent years as a way to enable local consumers/prosumers to trade their energy locally in a distributed and highly secured manner in an LEM. However, there are still some challenges regarding the main factors that can drive local consumers/prosumers to participate in a blockchain-based LEM, optimal community size, and prosumer to consumer ratio for an efficient LEM. Also, there is still no information on how the quantifying factors for participation on a blockchain-based LEM can affect the performance of an LEM. This paper presents a survey and simulation based analysis of quantifying factors for participation in a blockchain-based LEM. The survey was distributed among local consumers/prosumers and a total of 261 responses were received from the responders. The results from the responders were analyzed using a Python code based statistical analysis model. The simulation based analysis was conducted using a community based LEM model and evaluated using data received from a combination of German household profiles and standard load profiles. The survey results showed that the major drive for local consumers/prosumers to participate on blockchain-based LEM is their willingness to support renewable energy integration, transparency, and trust offered by a blockchain network. On the other hand, the simulation based analysis showed that small and medium communities with prosumers to consumer ratios between 0.3 to 0.5 create more economic and technical benefits for local consumers/prosumers compared to large communities. The community based simulation results were modelled together with the survey results to determine how the individual quantifying factors for participating in a blockchain-based LEM can affect the performance of an LEM.

INDEX TERMS Blockchain, decentralized energy system, survey analysis, local energy market, multi agent system.

I. INTRODUCTION

A. MOTIVATION AND BACKGROUND

Local energy markets (LEMs) were introduced in the last few decades as a result of the challenges arising from increasing distributed renewable energy resources and to enable small-scale producers, prosumers, and consumers to become involved in the electricity market [1]. LEM has also achieved quite a loud interest in countries such as Germany where there is high support for renewable energy integration because of the ability of LEM to support local renewable energy integration and create more savings for distributed energy resources owners [2]. In recent times, distributed ledger technologies (DLTs) are reshaping the conventional ideas of business transactions and have caught the interest of researchers on how the different DLT features can be applied to the energy sector and LEMs in particular [3]. DLT is an information systems that use protocols to record, validate, update, and

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access record of transactions across a decentralized network of computers nodes and has intrinsic mechanisms of enforcing consensus among the nodes [4], [5]. The features of DLT that made it attractive in different industrial sectors including energy sector are decentralized database structure, consensus mechanism, immutability, transparency, anonymity, and high security [6], [7]. Recent research works has shown that DLT has the potentials to enable prosumers and consumers within a community to trade energy in a secure manner [8], [9]. Because of its data structure, consensus mechanism, and high data security, blockchain has achieved high popularity, applied in many use case, and usually discussed in most literature and research works compared to other DLT concepts such as Tangle and Hashgraph [4].

B. LITERATURE REVIEW

Among all the features of DLT, decentralized database structure is majorly utilized in the development of LEM platform [9], [10], [11]. Hence, most research works in the field of blockchain-based LEM are focused on decentralizing the data structure of the LEM platform. Reference [10] developed a full blockchain-based decentralized platform for peer-to-peer(P2P) energy trading in a day-ahead market. The concept of Merkle Patricia Tries is used in its real or modified form to develop an immutable blockchain platform for LEM [12]. Reference [13] proposed an immutable blockchain-based framework for negotiating an auction based P2P energy trading for a local community. The concept of consensus mechanism is widely discussed in literature and imminent in most DLT platforms, and blockchain-based LEM platforms [6]. The authors of [14] proposed a blockchain-based double sided auction LEM that enforces consensus among prosumers and consumers every time slot before the market is matched. Transparency is a blockchain feature that is usually discussed and implemented in LEM research works directly ensuring that all transaction data are visible to the participants. However, in real LEM projects, because of the regulations and data protection law, transparency is usually implemented in form of hashing [15]. Reference [16] proposed a blockchain-based solution to increase the transparency and integrity of P2P market platform. Immutability as a feature of blockchain is its ability to retain information without tampering with data in its platform. This feature always raise questions on the sustainability of blockchain for its application because of the large amount of gas required for complex calculations/transactions. The authors of [17] proposed a Cosmos sidechain network for trading energy in an LEM and showed that the platform is sustainable by applying it in a real case scenario of a small community in Switzerland. Notwithstanding the large knowledge already gained for blockchain application in LEM, researchers are still exploring the different blockchain features and the best way to apply them in LEM trading, hence, blockchain application for LEM is now growing beyond the maturity stage [18], [19].

On the other hand, the technical and economic analysis of LEM plays an important role on the deployment of LEM based on DLT. This is because, the knowledge of the economic and technical benefits that will arise from the market is required for a broad adoption in productive environments. For this reason, there are still few literature discussing and analyzing the technical and economic benefits of LEM. The authors of [20] analyzed the performance indicators for participation in LEMs and showed that bidding strategies have more effect on the performance of an LEM compared to adding more distributed energy resources into the local community. Reference [21] analyzed and discussed a decentralized P2P market and a centralized order book LEM with zero-intelligence and intelligent bidding strategies and showed that P2P markets with intelligent agents seem most advantageous compared to others. Reference [22] analyzed the effect of microgrid size and prosumer-consumer ratios to local self-consumption and self-sufficiency of a community. A multi and single layer LEM models were developed by [23] and evaluated using different LEM economic and technical performance indicators such as self-sufficiency, self consumption ratio and share of market savings to show the applicability of LEM. Reference [24] used data from system logs, surveys, and interviews to analyze interaction, acceptance, and participation of prosumers in a P2P LEM. The analysis of their results showed that P2P LEM has the capability to increase the salience of renewable energies and thus promote load-shifting activities. The outcome of the results from analysis, user behaviour and designs of LEM has stirred up different business models and pilot projects in the field of blockchain-based LEM [25], [26].

Notwithstanding different research works already published in the field of blockchain-based LEM and different pilot LEM projects, in overall, only a small fraction of all LEM projects have been developed with blockchain technologies. The few projects already developed in the field of blockchain-based LEM are the Brooklyn microgrid [27], the Landau project [28] and the Allgäu microgrid [29].

C. CONTRIBUTIONS AND ORGANISATION

The literature contains several studies proposing different structures and models for blockchain-based LEMs, however, there is still a gap in literature determining or analyzing the major factors that can make a prosumer or consumer participate in an LEM trading, the optimal community size, production-to-consumption ratio, and prosumer-to-consumer ratio for an efficient LEM. Furthermore, there still exist no literature discussing how the quantifying factors for participating in a blockchain-based LEM can affect the performance of an LEM. Hence, this work is aiming to determine the quantifying factors for participation on local electricity markets based on distributed ledger technologies and the necessary conditions for most beneficial LEM. We use two step methods of survey and community based simulation analysis. In the first step, a survey was distributed to prosumers/consumers and energy experts requesting answers from them on their willingness and their main driving factors to participate in an LEM and in an LEM based on blockchain technology. The survey received 261 responses and the results were evaluated using statistical analysis. In the second method, a single layer community based LEM model was developed and simulated for varying community sizes and prosumer to consumer ratios. The simulation model was evaluated using key performance indicators such as self-sufficiency, self-consumption ratio, share of market savings, share of consumer savings and share of prosumer savings. The prosumers and consumers also known as local electricity traders (LETs) are classified as household consumers, commercial consumers, household prosumers, and commercial prosumers. The main contributions of the paper can be summarized as follows:

- We develop and distribute a survey to investigate on quantifying factors to participate in LEM and blockchain-based LEM.
- The results from the survey were analyzed to determine the driving factors to participate on LEM and blockchain-based LEM.
- We conduct a simulation for a single layer LEM model with varying community sizes and prosumer to consumer ratios.
- We analyse the benefits of electricity trading in a single layer LEMs model with the use of key performance indicators such as self-sufficiency, self-consumption, and share of market savings.
- We modelled the quantifying factors for participanting in a blockchain-based LEM determined from survey together with the simulation results to determine how the different quantifying factors can affect the individual LEM performance indicators for a community based LEM.

The remaining sections of this work are structured as follows. The developed survey and analysis methods are described in Section II. The survey and simulation results are analyzed in Sections III-A and III-B, respectively. Finally, the paper is concluded in Section V.

II. ANALYSIS METHOD

In order to analyze the acceptability, willingness, interests, motivation, technical, and economic indicators that may enable prosumers to participate in a blockchain-based LEM, the analysis method is classified into survey and simulation based analysis.

A. SURVEY BASED ANALYSIS

For this method, a survey was conducted and shared among German households to illustrate their willingness, interest and social behaviour towards a blockchain-based LEM. Our approach is based on a similar work in this field by [2], however, we create an extensive study to analyze the different factors individually and their relation to LEM application with blockchain. Appendix A-A shows the survey questions.

TABLE 1. Age range of survey responders.

S/N	Age range (Years)	Number of responses
1	Under 30	34
2	30 - 50	82
3	Above 50	71

TABLE 2. Net income salary range of survey responders.

S/N	Salary range (Euro per annum)	Number of responses
1	Under 35,000	46
2	35,000 - 50,000	50
3	Above 50,000	88

The questions were developed and displayed online using SurveyMonkey and the web link to the questions distributed to responders. Fig. 13 displays a screen shoot of part of the survey questions on SurveyMonket website. The link to the questions was distributed using different online platforms such as LinkedIn, Slack channels, Xing and Emails. With Emails, it was sent directly to 400 customers of e-regio, a German electricity retail company using their contact Email. The survey takes approximately 12 minutes to complete it. The survey was opened online on SurveyMonkey website from 15th August until 20th December 2021 and it received a total of 261 responses. However, the responses were filtered down to 232 due to incomplete answers. Table 1 and 2 display the age and net income range of the responders, respectively. From the survey response response, 40.5% of the responders live in rented apartments/buildings, 57.8% live in their own house/apartments while 1.6% did not specify where they live.

B. SIMULATION BASED ANALYSIS

The simulation based analysis is based on the works of [20] and [23]. A single layer local electricity market as developed by [23] is simulated for varying community sizes, number of prosumers to total participants (nPP) ratio, and annual production-to-consumption ratio (PtC). Fig. 1 [23] displays the single layer local electricity market model where prosumers and consumers trade electricity within the local energy markets, electricity not traded within the LEM is traded with the upstream grid by the community agent.

Each household is represent by an agent which is responsible for making the bidding/offering of the household electricity every time slot, on behalf of the consumer or prosumer. At every market slot $(t-1)$, the consumer agent (i) posts a bid containing the quantity of electricity $(q^b_{i,t})$ in kWh the consumer wants to buy and the maximum price $(p^b_{i,t})$ the consumer is willing to pay per kWh of electricity for the next time slot (t), as shown in Eq. (1), to the community market platform.

$$b_{i,t} = \{q^b_{i,t}, p^b_{i,t}\}, \forall t. \tag{1}$$

In the same way, at $t-1$, the prosumer agent (j) posts an offer containing the quantity of electricity $(q^s_{j,t})$ in kWh the prosumer wants to sell and the minimum price $(p^s_{j,t})$ the prosumer is willing to receive per kWh of electricity for the

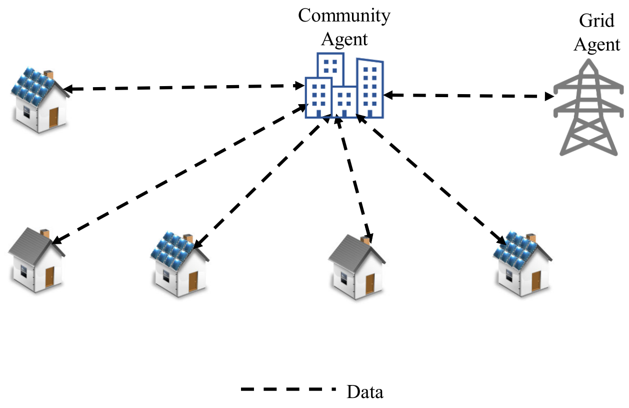


FIGURE 1. Single layer local energy market framework.

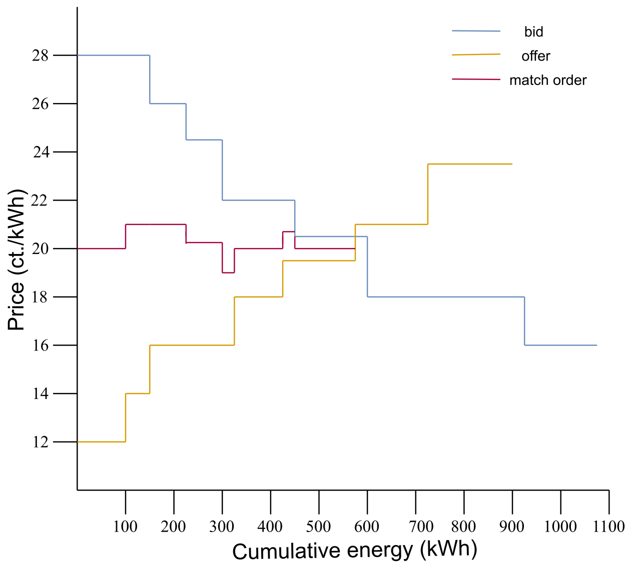


FIGURE 2. Two sided clearing mechanism with discriminative pricing.

next time slot (t), as shown in Eq. (2), to the same community market platform.

$$s_{j,t} = \{q^s_{j,t}, p^s_{j,t}\}, \forall t. \tag{2}$$

Eqs. (3) and (4) represents all the bids and offers posted to the market platform at time $t-1$ for energy exchange that will happen at time t. $\mathcal{K}$ and $\mathcal{N}$ are the total number of bids and offers, respectively.

$$B_t = \{b_{1,t}, \ldots, b_{\mathcal{K},t}\}, \quad \forall t. \tag{3}$$

$$S_t = \{s_{1,t}, \ldots, s_{\mathcal{N},t}\}, \quad \forall t. \tag{4}$$

The market is matched at the end of the time slot ($t-1$). The clearing mechanism is a two sided pay-as-bid market clearing mechanism with discriminative pricing. The community local grid fee (g) which is the fee the buyer pays for buying electricity from the LEM is first subtracted from the maximum price ($p^b_{i,t}$) the buyer is willing to pay to determine the bid price ($p^{b*}_{i,t}$) as shown in Eq. (5). The minimum price ($p^s_{j,t}$) the seller is willing to receive is the offer price.

$$p^{b*}_{i,t} = p^b_{i,t} - g, \quad \forall i, t. \tag{5}$$

The bids and offers are arranged in descending and ascending orders of bid and offer prices, respectively. Then, the bids and offers are matched one after the other until the intersection of the bidding and offering prices which after, the offer price is higher than the bidding price as shown in Fig. 2. The matched price ($p^m_{i,j,t}$) is the average of the bidding and offering prices. This is the price the seller j will receive for each kWh of its energy matched in the LEM with buyer i. This can also be referred to as the sold price. The matched price is represented in Eq. (6),

$$p^m_{i,j,t} = \frac{p^{b*}_{i,t} + p^s_{j,t}}{2}, \quad \forall i, j, t. \tag{6}$$

The bought price ($p^b_{i,j,t}$) is the price the buyer i pays per kWh of electricity bought from the LEM from seller j. This is the sum of the matched price and the grid fees (g) as presented in (7),

$$p^b_{i,j,t} = p^m_{i,j,t} + g, \quad \forall i, j, t. \tag{7}$$

At the end of the market clearing, electricity not traded within the LEM is bought/sold from/to the upstream grid using the grid price/feed-in tariff price. The trading strategy is a random trading strategy where the participants randomly select a bid/offer price within the range of the feed-in tariff price of 11.0 ct/kWh to the grid electricity price of 32.0 ct/kWh. The grid electricity price is capped at 32.0 ct/kWh because of the average cost of household electricity in Germany for the year 2021 [30]. The buyers' bid price include the metering and local grid fee of 0.33 ct/kWh and 4.0 ct/kWh, respectively. This sets the lowest price electricity can be exchanged between buyers and sellers within the LEM at a buying price of 15.33 ct/kWh.

The simulation is varied by changing the community size from a total of 10 to 120 participants in 238 simulation scenarios. The different simulation scenarios are further obtained by varying the PtC ratio of the LEM participants. Table 3 shows the various community types, the number of participants per community type, the community classification, and the number of simulation per community type. For the large communities, the simulation scenarios are obtained by varying the nPP ratio from 0.1 to 0.9 with a step of 0.1 and varying the PtC ratio from 0.2 to 1.4 with a step of 0.2. However, for the medium and small communities, the simulation scenarios are obtained by varying the nPP ratio from 0.3 to 0.6 with a step of 0.1 and varying the PtC ratio from 0.2 to 1.4 with a step of 0.2. From Table 3, the number of participants is the total number of consumers and prosumers within the community. Each prosumer or consumer within the community is referred to as local electricity trader (LET).

The simulation data are load profiles obtained from combination of profiles from [31], LoadProfileGenerator [32], [33], and standard load profiles [34], [35]. Table 4 displays how the different commercial and industrial participants such

TABLE 3. Simulation set-up for different community types.

S/N	Community type	No. of Participants	Community class	No. of scenarios
1	A	120	Large comm.	63
2	B	100	Large comm.	63
3	C	75	Medium comm	28
4	D	50	Medium comm	28
5	E	20	Small comm	28
6	F	10	Small comm	28

TABLE 4. Arrangement of industrial and commercial LETs in the different community types.

S/N	Community type	Small manufacturing firm with PV	Bakery	Office buildings with PV
1	A	6	6	15
2	B	6	6	10
3	C	4	4	5
4	D	4	4	5
5	E	2	2	3
6	F	-	1	1

as office building, bakery and small manufacturing firm are added to the different community types. The standard load profiles from Stromnetz Berlin for the year 2021 are used for commercial and industrial profiles [34]. The range of the annual consumption of the commercial profiles is between 25,000 kWh and 30,000 kWh, while for the industrial profiles, it is between 49,000 kWh and 54,500 kWh. To ensure that each LET is unique, a random error in the range of 5–20% was added to each time step of every commercial and industrial profile. The PV production profiles are profiles from Renewables Ninja [36], [37] using the Stuttgart region as the geographic location of the community. The losses of the PV systems were varied between 5% and 15% with a tilt angle of 35°. To ensure that all the seasons of the year are contained within the simulation, the simulation was done for the month of January, April, July and October.

III. RESULTS AND DISCUSSIONS

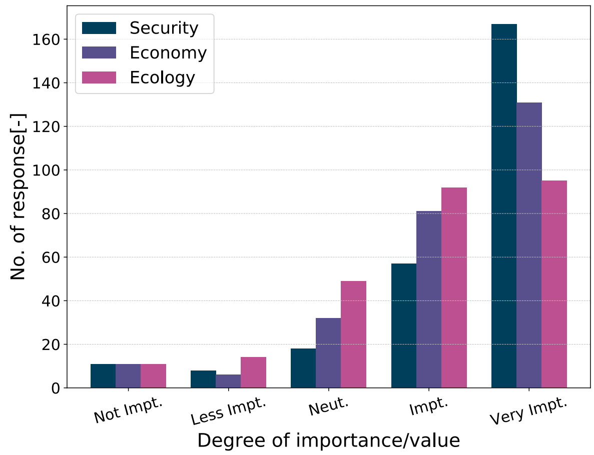
A. SURVEY ANALYSIS

In this section, the results from the survey described in Section II-A are presented and analyzed according to the environmental and energy policy, willingness and interest in LEM, affinity for and trust in new technology and importance of blockchain features.

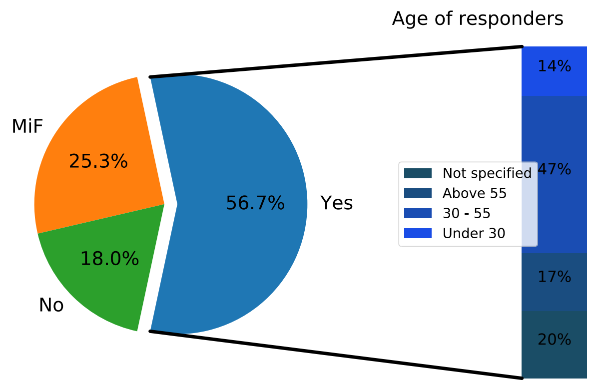
1) ENVIRONMENTAL PROTECTION AND ENERGY POLICY

Fig. 3 displays the level of willingness of the participants to support environmental protection, security of supply and economic value for energy sources. From Fig. 3a, the participants attributed high level of importance on the three elements of energy policy which are security of supply, economy and ecology. However, security of supply is of strong importance to the participants followed by economy before ecological advantage/value. This means that the future LEM participants are mostly interested in ensuring that the source of supply is secured and thereby having energy available at all times. After this is provided, then, making financial benefits from their LEM is of importance to them before supporting their environment.

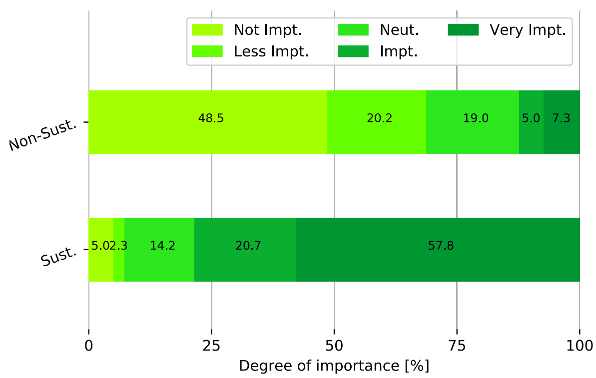
Fig. 3b displays the level of willingness of the participants to pay more for their renewable energy resources. From the diagram, 56.0% of the participants are interested in paying more for their renewable, 18.0% are not interested and 25.3% are interested in paying more may be in the future (MiF). This is evidence that majority of the participants whom are



(a) Importance of ecology, economy and security of supply

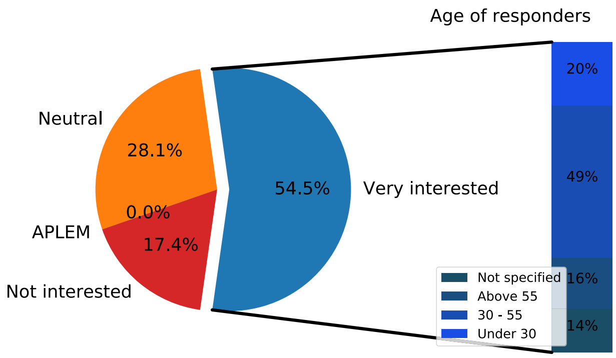


(b) Willingness to pay more for renewable energy

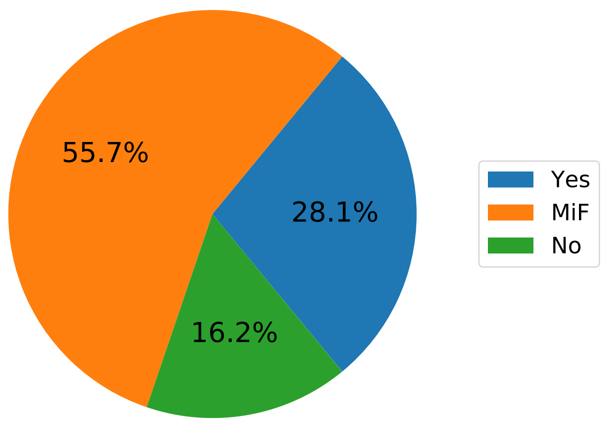


(c) Preferable source of energy

FIGURE 3. Level of willingness to support environmental protection, security of supply and economic value for energy sources.



(a) Level of interest in LEM



(b) Willingness to join LEM pilot project

FIGURE 4. Interest in LEM and willingness to join LEM pilot projects.

mostly within the age of 30 to 55 years are willing to pay more money to ensure that they have more renewable source of energy. Fig. 3c displays the preferable energy sources of the participants. From the diagram, it is evidence that majority of the participants which are more than 70.0% prefer renewable energy as their source of energy.

2) WILLINGNESS AND INTEREST IN LEM

Fig. 4 displays the level of willingness and interest of the participants to join LEM and LEM pilot projects. The diagram in Fig. 4a shows that 54.6% of the participants are very interested in joining LEM, 28.1% are neutral to joining LEM and 17.4% are not interested in joining LEM. On the other hand, no one (0.0%) is already part of LEM (APLEM). This means that majority of the participants are interested in joining LEM. Fig. 4b shows the level of willingness of the participants to join an LEM pilot project. From the diagram, it can be seen 28.0% of the participants are interested in joining pilot projects, 16.2% are not interested in joining pilot projects while 55.7% are interested in joining pilot projects may be in the future (MiF). This is evidence that even though most participants are willing to join LEM, a majority is not yet ready to join.

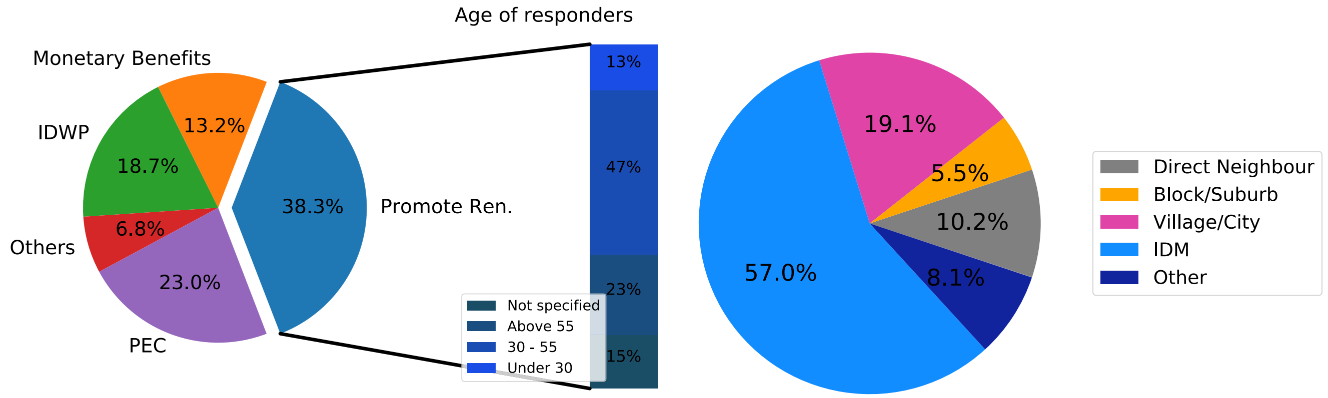
Fig. 5 displays the results of why the participants would like to join LEM and it also shows which trading partner they would prefer. From Fig. 5a, 38.3% would like to participate in an LEM in other to promote renewable (Promote Ren.) energy resources, 13.2% are willing to join for monetary benefits, 23.0% are willing to join because they want to be part of energy community (PEC), 18.7% do not want to participate (IDWP) in LEM and 6.8% have their personal reasons of wanting to join LEM. From the diagram, it is evidence that the major drive for prosumers and consumers to join LEM is to promote renewable energy trading and to be part of energy community. Only a few percentage of the participants wish to join LEM because of the monetary benefits. Fig. 5b displays the preferable trading partners of the participants. From 5b, 10.2% of the participants are willing to trade with their direct neighbour, 5.5% are willing to trade with people living within their block, 19.1% are willing to trade with people living within their village/city and 57.0% does not mind (IDM) who their trading partner is. 8.1% of the participants have different choice of trading partners such as friends and family members. The diagram shows that majority of the participants do not care who their trading partners are or should be but only care about the type of energy they consume.

3) AFFINITY FOR AND TRUST IN NEW TECHNOLOGY

The blockchain solution for LEM comes with new technology such as energy software applications, smart metering devices, and intelligent batteries. Hence, there is a need to access the participants willingness, interest, and trust for new technology that will follow the deployment of a blockchain-based LEM. Fig. 6a displays the level of importance of new technology (INT) to the participants. From the diagram, while 40.5% of the participants show that new technology is important to them, only 21.4% ranked new technology to be extremely important to them. This shows that new technology is not very important to the participants. Fig. 6b displays the level of trust on new technology (TINT) in an LEM by the participants. From the diagram, majority of the participants are neutral to new technology and only shows a low level of trust to new technology. This shows that before the deployment of blockchain-based LEM model, there is a need to engage the participants in order to let them know the importance of new technology and to increase their level of trust for new technology.

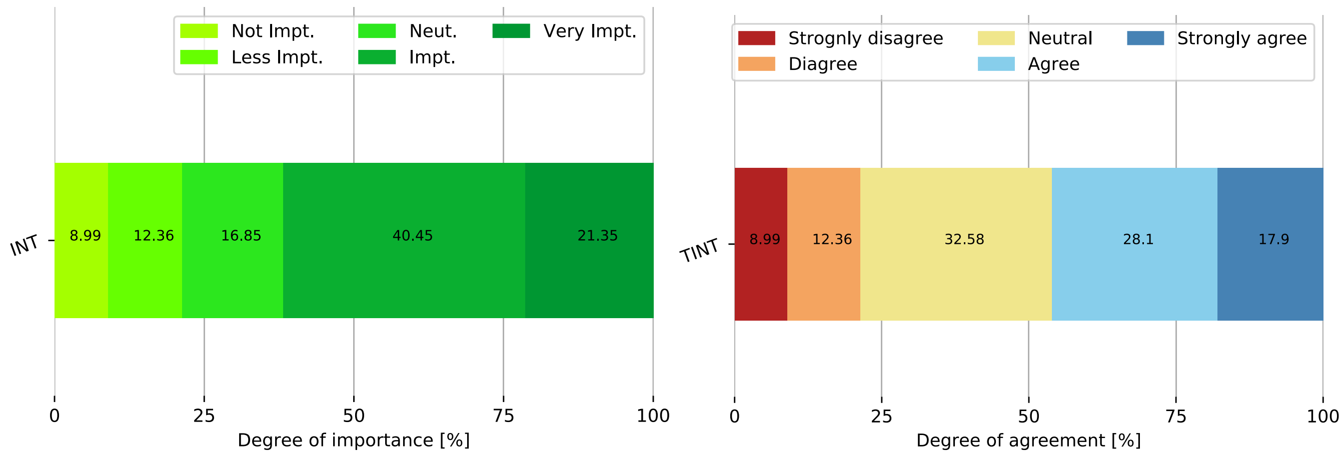
4) IMPORTANCE OF BLOCKCHAIN FEATURES

Blockchain comes along with new features such as alternative method of payment (cryptocurrency), immutability (Immu.), anonymity (Anon.), transparency (Trans.), decentralization (Decen.) and trust. The section evaluates the importance of these blockchain features to LEM participants. Fig. 7a displays the results of the participants' willingness to use an alternative payment method for trading their energy.The participants are open to blockchain technology in a similar way as they are open to new technologies in general as obtained in Fig. 6. Thus, it is evidence that majority of the participants are neutral towards using alternative mode of payments. This



(a) Major reason to participate in LEM (b) Preferable trading partner in LEM

FIGURE 5. **Reason to join LEM and preferable trading partner.**



(a) Level of importance/interest in new technology (b) Level of trust for new technology

FIGURE 6. **Level of interest and trust for new technology in LEM.**

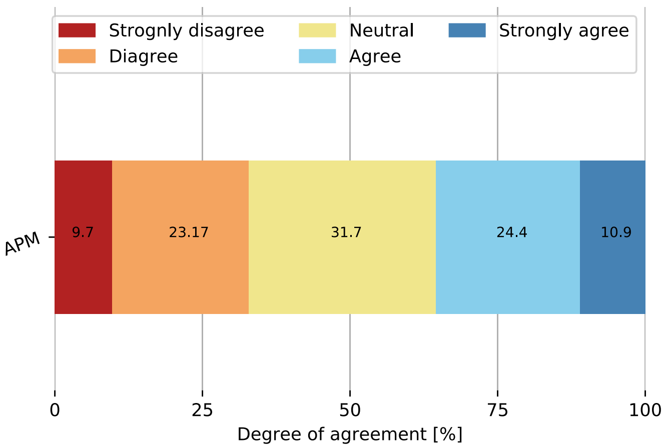
also means that to deploy blockchain-based LEM to the participants, there is a need to inform them and create awareness for them about the importance and benefits of alternative means of payments. Fig. 7b displays the level of importance attributed to the features of blockchain by the participants. The diagram shows that the participants attribute more importance to blockchain features such as trust, transparency and immutability than to anonymity and decentralization. Hence, in the design of LEM, it will be important to focus on utilizing these major features that form the bedrock of the willingness to participate in LEM trading based on blockchain technology.

B. COMMUNITY BASED SIMULATION ANALYSIS

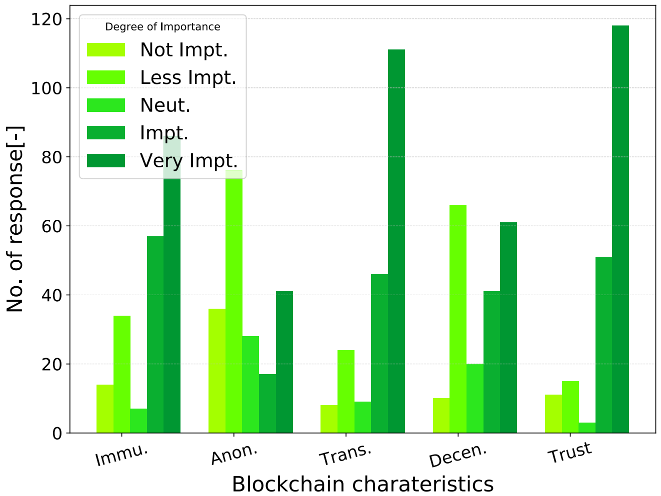
In this section, the community based simulation results of Section II-B are presented and analyzed. First, the technical and economic performance indicators of the large communities are presented and discussed. Afterwards, the indicators are compared with the different community sizes. Finally, the energy exchange within and outside the communities is compared and analyzed.

1) ANALYSIS OF TECHNICAL PERFORMANCE INDICATORS OF LARGE COMMUNITIES

Fig. 8 displays the self sufficiency (SS) and self consumption (SC) ratios of the large communities for varying PtC and nPP ratios. From Figs. 8a and 8c, it can be seen that the SS of communities A and B show similar characteristics for varying nPP and PtC ratio. The SS of community A ranges from 20.3% at nPP and PtC ratios of 0.1 and 0.2, respectively to 48.3% where the nPP and PtC ratios are 0.9 and 1.4, respectively. In the same way, SS of community B ranges from 19.7% at nPP and PtC ratios of 0.3 and 0.2, respectively to 47.6% where the nPP and PtC ratios are 0.3 and 1.4, respectively. Therefore, on average, community A shows better SS compared to community B. This is because the higher number of LETs in community A creates opportunity for trading more energy within the local community instead of buying from the upstream grid. Also, for communities A and B, increasing the PtC ratio increases the SS for community A and B. This is because increasing PtC ration means adding more renewable generated energy within the community which in turn helps to increase local consumption and



(a) Willingness to use alternative payment method



(b) Level of importance of blockchain features

FIGURE 7. Importance of blockchain features for LEM.

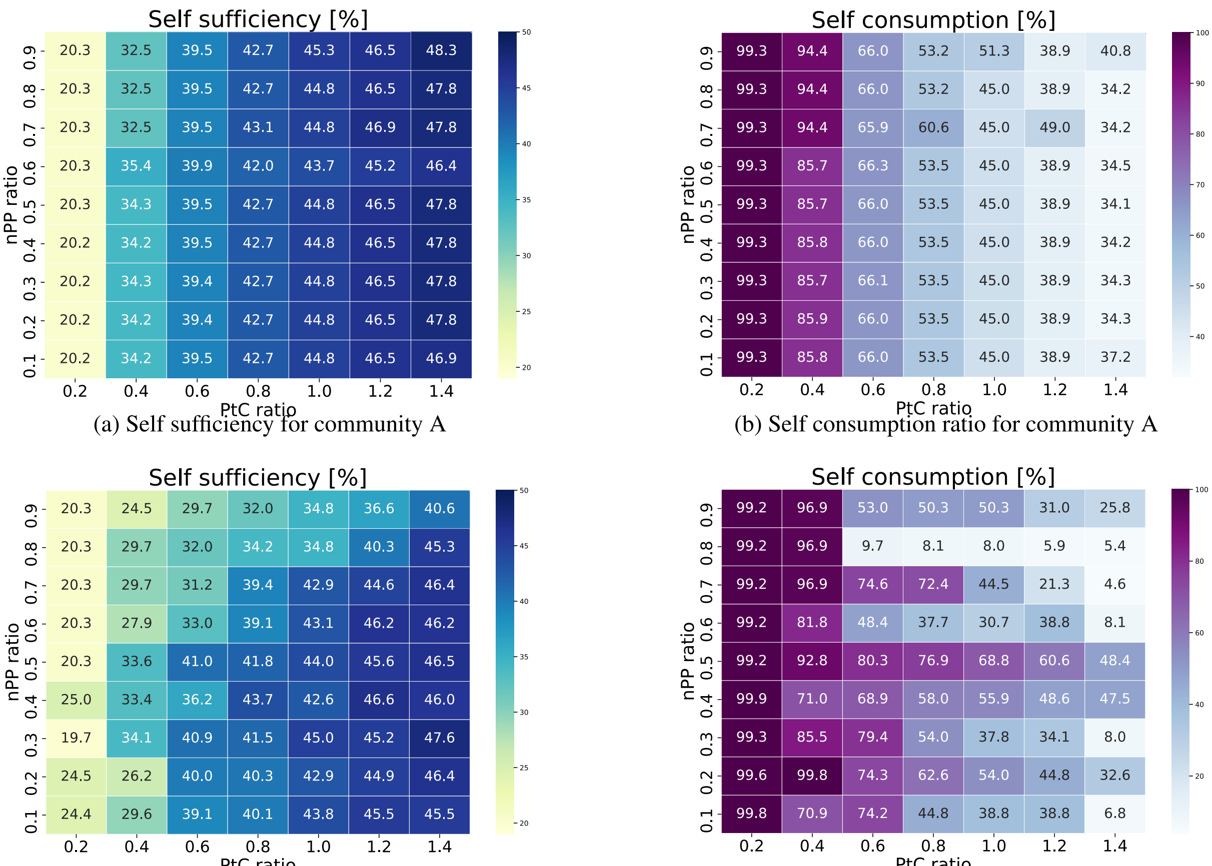
thereby increasing the community SS. On the other hand, the nPP has little impact on the communities which can be noticed in community B. From community B (Fig. 8c), nPP ratio within the range of 0.3 to 0.6 offers higher SS to the local community compared to others. This is illustrated in Fig. 8c, the SS increase from [19.7, 25.0] % at PtC ratio equal to 0.2 to [46.0, 47.6] % at PtC ratio equal to 1.4. Hence, the SS becomes higher as the nPP ratio moves close to 0.4. This is evidence that the nPP ratio has an impact on the performance of LEM.

Figs. 8b and 8d display the SC of communities A and B, respectively. Similar to SS, the SC of communities A and B show similar characteristics for varying nPP and PtC ratio. The SC of community A ranges from 34.1% at nPP and PtC ratios of 0.5 and 1.4, respectively, to 99.3% where the PtC ratio is 0.2. Similarly, the SC of community B ranges from 5.4% at nPP and PtC ratios of 1.4 and 0.8, respectively, to 99.9% where the nPP and PtC ratios are 0.4 and 0.2, respectively. Hence, increasing the PtC ratio decreases the community SC ratio for communities A and B. This is because, increasing the PtC ratio means adding more renewable to the local community, therefore, there is a higher likelihood that at high PtC ratio, all the energy generated within the local community will not be consumed thereby decreasing the SC ratio of the local community compared to when a lower renewable energy is generated. Therefore, the self SC rate increases with decreasing availability of renewable energy within the community. The nPP ratio has little impact on community A. This is because, the higher number of LETs in community A reduce the effect of varying the nPP ratio. As it can be seen in community B (Fig. 8d), nPP ratio within the range of 0.3 to 0.6 leads to a higher SC ratio of the community. This is evidence that reducing the community size reveals the impact of the nPP ratio to the LEM.

2) ANALYSIS OF ECONOMIC PERFORMANCE INDICATORS FOR LARGE COMMUNITY

Fig. 9 displays the share of market savings (SMS) of communities A and B and the share of individual savings (SIS) of household consumer 1 (C1) and household prosumer 1 (P1) for participating in communities A and B. The community SMS is the share of savings made by the LETs for trading within the LEM compared to when there is no LEM [23]. On the other hand, the share of individual savings is the percentage savings made by the individual LET for trading within the LEM compared to when there is no LEM [23]. Figs. 9a and 9b display the SMS of the communities A and B, respectively. From the diagrams, the SMS of the two communities show similar behaviours for varying PtC and nPP ratios. The SMS of community A ranges from 8.9% at nPP and PtC ratios of 0.1 and 0.2, respectively, to 59.9% where the nPP and PtC ratios are 0.2 and 1.4, respectively. Similarly, the SMS of community B ranges from 9.0% at nPP and PtC ratios of 0.2 and 0.2, respectively, to 58.9% where the nPP and PtC ratios are 0.3 and 1.4, respectively. Hence, increasing the PtC ratio of a community increases the SMS of the community. Increasing the PtC ratio of a community means adding additional renewable resources to the community. Adding more renewable generated resources to the community creates more financial benefits to the local community. On the other hand, varying the nPP ratio only has little impact on the local communities. In community A, for PtC equals 0.2, varying nPP from 0.1 to 0.9 only changed the SMS from 8.9% to 12.1%. Similarly, for community B, for PtC equals 0.2, varying nPP from 0.1 to 0.9 only changed the SMS from 9.0% to 12.2%. For both communities (Figs. 9a and 9b) a higher SMS is witnessed at high PtC ratio with nPP ratio between 0.2 to 0.6.

Figs. 9c and 9d display the SIS of C1 in communities A and B, respectively for varying PtC and nPP ratios. The



(a) Self sufficiency for community A

(b) Self consumption ratio for community A

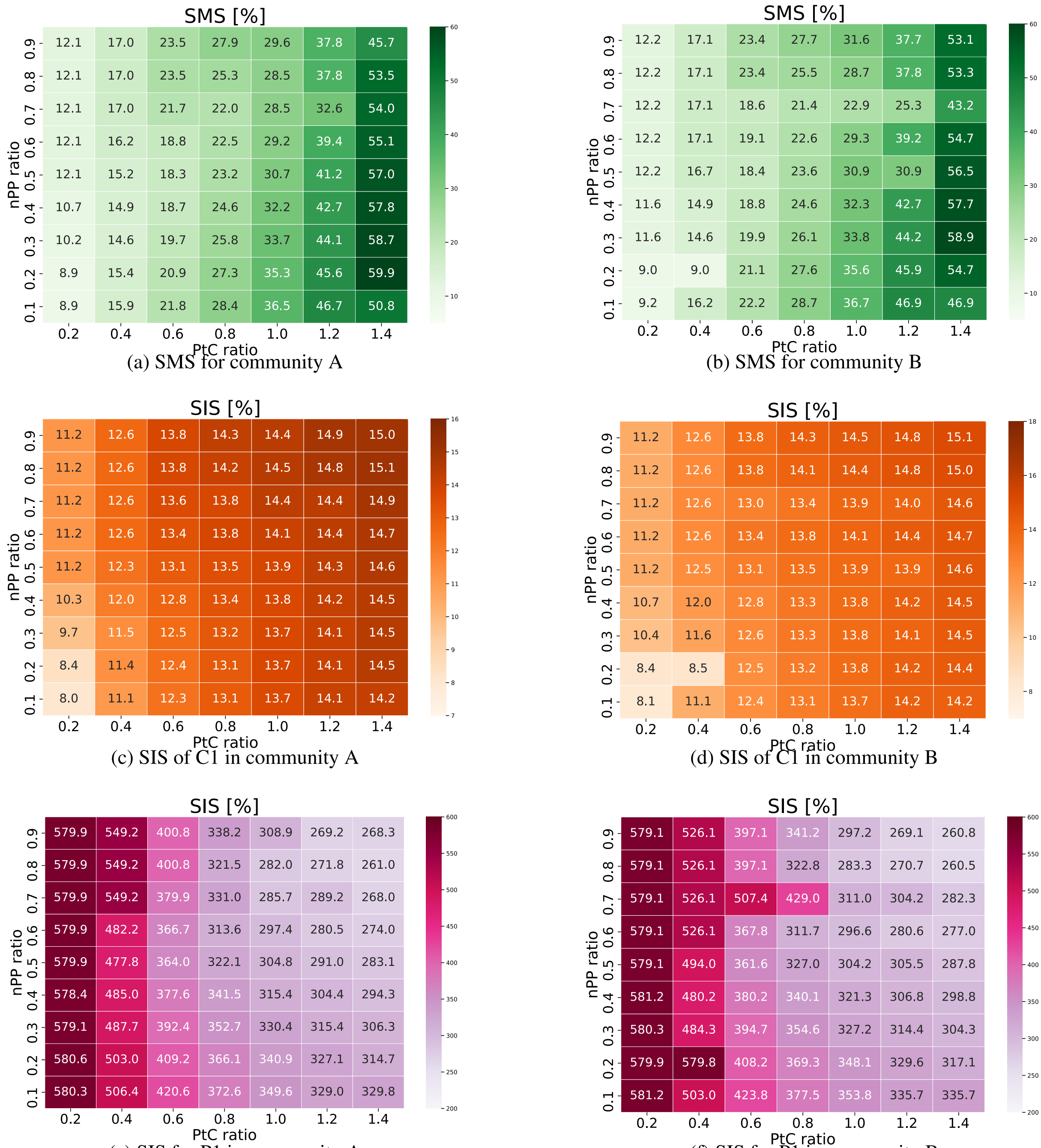
(c) Self sufficiency for B community

(d) Self consumption for B community

FIGURE 8. Community self sufficiency and self consumption ratio for varying PtC and nPP ratio.

two communities show the same trends for SIS of C1 with varying PtC and nPP ratios. However, in community A, the average SIS of C1 is 13.2% which is a bit higher than the average SIS of C1 in community B which is at 13.0%. This is because the LETs in community A is higher than community B thereby creating additional opportunities for C1 to buy their energy. For both diagrams, increasing the PtC ratio increases the SIS of C1. This is because C1 is a consumer, thereby increasing PtC ratio creates opportunity for the consumer to buy more renewable from the community thereby increasing his/her share of savings. In the same way, increasing the nPP ratio increases the SIS of C1. Increasing nPP means adding more prosumers to the community. Since C1 is a consumer, adding more prosumers to the community even at constant PtC ratio creates more opportunities for the C1 to have variable options on whom to buy energy from thereby increasing their financial benefits from the LEM.

Figs. 9e and 9f display the SIS of P1 in communities A and B, respectively, for varying PtC and nPP ratios. Similar to SIS of C1, the two communities show similar features for varying PtC and nPP ratios. However, unlike C1, in community A, the average SIS of P1 is 388.2% which is lower than the average SIS of P1 in community B which is at 394.5%. This can be because of the higher number of prosumers in community A which make the community A LEM more compaetitive for P1 compared to community B where there are less prosumers and thus provides opportunity for P1 to trade most of their produced energy. Also, the range SIS of P1 (Figs. 9e and 9f) which is [260.5, 580.6] % is higher than the range of SIS of C1 (Figs. 9c and 9d) which is [8.0, 15.1] % because of the investment made by the prosumer by purchasing PV for trading in the LEM. Figs. 9e and 9f show a decrease in SIS of P1 for increasing PtC and nPP ratios. For example, at constant nPP of 0.2, for community A, increasing the PtC ratio from 0.2 to 1.4 decreases the SIS of P1 from 580.6% to 314.7%. Similarly, for community B, increasing the PtC ratio from 0.2 to 1.4 decreases the SIS of P1 from 579.9% to 317.1%. Increasing the PtC ratio decreases the SIS of P1 because, increasing PtC ratio means increasing the PV production of the community without increasing the PV generation of P1. This eventually creates competition for P1 as most other LETs within the community will produce electricity thereby potentially reducing trading opportunities of P1 and in overall the financial benefits of P1 from the LEM. In the same way, increasing the nPP ratio means adding more prosumers to the community without increasing the number of consumers. This eventually will create more competition for P1 thereby reducing its benefits from the markets.



(a) SMS for community A

(b) SMS for community B

(c) SIS of C1 in community A

(d) SIS of C1 in community B

(e) SIS for P1 in community A

(f) SIS for P1 in community B

FIGURE 9. Economic indicators for varying PtC and nPP ratio.

Fig. 14 in Appendix C displays the SIS of a commercial consumer (C4) and commercial prosumer (P5). Overall, the SIS of both LETs show similar trends to the household consumer and prosumer. However, on an average, the SIS of the commercial consumer (C4) is higher compared to the household consumer(C1) while the SIS of the household prosumer(P1) is higher compared to the commercial prosumer (P5) for the same PtC and nPP ratios. This is because, an LEM creates opportunity for a commercial consumer to buy electricity at a cheaper price within their neighbourhood thereby reducing his/her electricity cost. Since the energy consumption of a commercial consumer is higher than that of a household consumer, the commercial consumer will benefits more from the market since he/she would buy more energy from the LEM. However, for a commercial prosumer participating in the same LEM with a household prosumer, the probability that the household will sell their energy production is higher compared to a commercial consumer who has more energy to sell. Hence, the household prosumer will have higher SIS compared to a commercial prosumers who need to sell a lot of energy to equate their investment before he/she can make an equal SIS. This notwithstanding, the savings of the commercial consumer may be higher than the household consumer.

3) COMPARISON OF TECHNICAL INDICATORS BASED ON COMMUNITY SIZES

To further understand the effect of community size on the LEM performance indicators, the experiments were repeated for varying PtC ratio from 0.2 to 1.4 and nPP ratio from 0.3 to 0.6 for communities A to F as described in Tables 3 and 4. Fig. 10 displays the SS of the different communities for varying PtC and nPP ratios. The graphs of Fig. 10 display similar characteristics for increasing PtC ratio. Thus the SS of all communities at the different nPP rations increase from 19.0% at PtC ratio equal to 0.2 to about 50.0% at PtC equal to 1.4. Thus, at low PtC ratio, there is low renewable production within the communities thereby making the LETs to depend on upstream grid for their energy demand and thus having low SS. From Figs. 10a and 10b, the community SS increases swiftly with increasing PtC ratio. Also, small and medium communities show better SS compared to large communities. Thus at PtC equals to 0.2, the SS of the small/medium community is about 25% where as the SS of the large community is at about 20%. At all PtC ratios, the SS of small and medium communities are usually higher than that of the large community even until the maximum PtC where the SS of the small community is about 50%. At the same time, the SS of the large community is about 46%. Thus, for a small or medium community, with the nPP equals to 0.3 or 0.4, it is easy for the LETs to exchange energy at optimal level ensuring that all energy produced within the community is consumed within the community. This is compared to a large community where the exchange may be difficult to manage resulting in exchanging energy with the upstream grid. For Figs. 10c and 10d, the community SS of all communities show similar behaviours to Figs. 10a and 10b and within the same range of between 19 to 50 %.

Fig. 15 in Appendix C displays the community Self consumption (SC) ratio for varying community sizes, PtC and nPP ratios. Similar to the SS, the SC ratio graphs of Fig. 15 show similar variation for varying PtC ratio. The SC with nPP equal 0.3, 0.4 and 0.5 varies from 100% at low PtC ratios to about 34% at high PtC ratios. For nPP equals to 0.6, the SC varies from 100% at low PtC ratios to about 8.4% at high PtC ratios. Hence, increasing the PtC ratio decrease the community SC ratio. This is because, at lower PtC ratio, the energy production within the local community is low and therefore, there is higher tendency that majority of the energy will be consumed within the community thereby not selling to external grid. Increasing the PtC ratio increases the locally produced energy and thereby reducing the probability that all the energy will be traded within the community and hence, reducing the SC ratio of the community by selling the energy produced within the community to the upstream grid. For varying nPP ratios, the graphs with nPP equal to 0.5 and 0.6 show better performance of the community SC ratio with community D showing the best performance at nPP equals 0.6. Community D is a medium community, therefore, organizing trade within such community where the LETs are not too much and where there is sufficient energy to be traded by the participants can result in higher community performance of the SC.

4) COMPARISON OF ECONOMIC INDICATORS BASED ON COMMUNITY SIZES

Figure 11 displays the community SMS for varying community sizes, PtC and nPP ratios. For all nPP ratios, the community SMS of the different communities increases with increase in PtC ratio. For all nPP ratios, the SMS of the small and medium communities varies within the range of 18 to 80 % for varying PtC ratios of from 0.2 to 1.4. On the other hand, the SMS of large communities varies within the range of 13 to 60 % for varying PtC ratios of from 0.2 to 1.4. Hence, for all nPP ratios, the medium and small communities show better performance for SMS compared to the large communities. This is evidence that the medium and small communities provide more economic benefits to the LETs because of the efficient organization of trade at this community size which resulted in more economic benefits compared to large communities. At nPP equals 0.4, all the medium and small communities have their best SMS performance apart from community E which has its best performance at nPP equal 0.5. For example, the SMS of community E at nPP equals to 0.4 varies from 20 % at PtC equals to 0.2 to 80% when the PtC ratio is 1.4. However, with nPP equals to.5, the SMS varies from 27% when the PtC ratio is 0.2 and reached the maximum SMS which is 80% when the PtC is 1.2.

Fig. 16 in Appendix C displays the SIS of C1 for varying community sizes, PtC and nPP ratios. The SIS of C1 show similar behaviour for all the communities and for all nPP ratios. The SIS show close range of values for increasing PtC ratios in the different communities. The range of SIS of C1 is from 8.5 % at a PtC ratio of 0.2 to 14.8 % at a PtC ratio of 1.4. The SIS of C1 achieves its optimum in community E when the nPP ratio is 0.5 with SIS varying from 12.5 % at a PtC of 0.2 to 14.8 % at a PtC of 1.4. Figs. 17, 18 and 19 of Appendix C display the graph of the SIS for P1, C4 and P5, respectively for varying community sizes, PtC and nPP ratios.

5) COMPARISON OF ENERGY EXCHANGE

Fig. 12 displays the energy exchange within and outside the local community for varying community sizes and nPP ratios. Because of the advantages of medium and small communities in the previous simulations, this section analyses the energy exchange of the medium and small communities for nPP ratio equals 0.3, 0.4 and 0.5. The internal traded energy is the energy traded between the LETs for the whole simulation time within the LEM. The energy import/export is the energy imported/exported from/to the upstream grid. From Figs. 12b and 12c, it is evidence that the external energy exchange

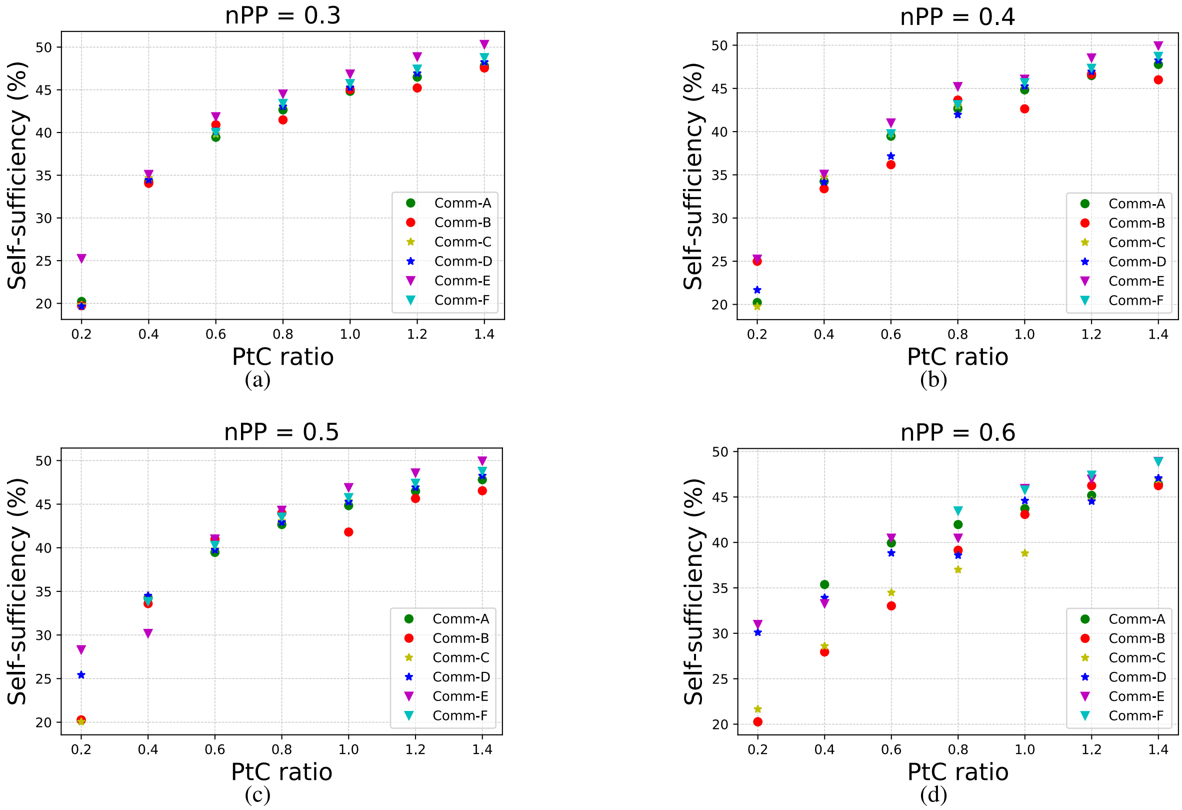


FIGURE 10. **Community self-sufficiency for varying PtC and nPP ratio, and community sizes.**

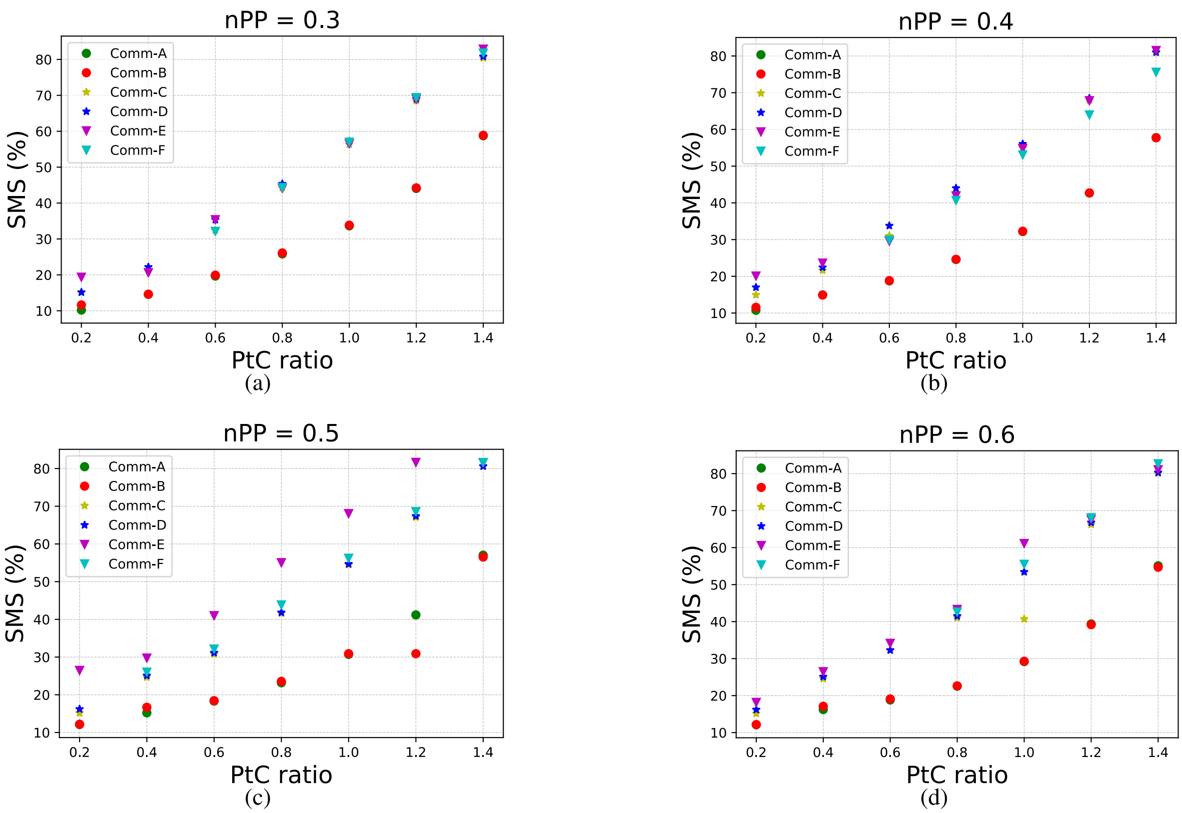
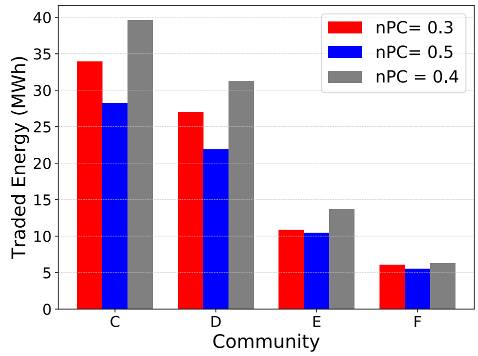
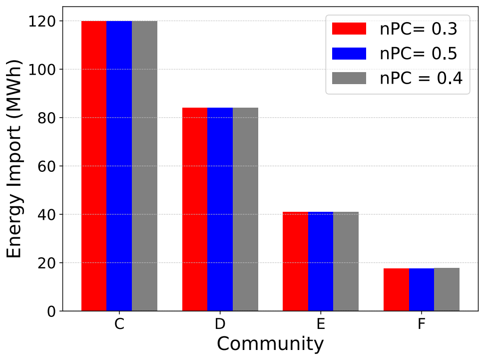


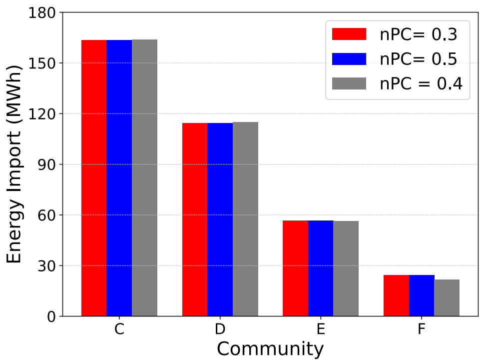
FIGURE 11. **Community SMS for varying PtC and nPP ratio, and community sizes.**



(a) Internal traded energy



(b) Energy import



(c) Energy export

FIGURE 12. Energy exchange within and outside the local community for varying nPP ratios.

with the upstream grid is relatively unaffected by the nPP ratio. Hence, the energy import is about 120 MWh, 85MWh, 40MWh and 17MWh for C, D, E, and F communities respectively. The nPP ratio affects mainly the internal energy exchange between the LETs as shown in Fig. 12a. From Fig. 12a, for all community types, nPP equals to 0.4 shows the maximum internal traded energy with an internal traded energy of about 40MWh in community C.

IV. EFFECTS OF LEM QUANTIFYING FACTORS ON PERFORMANCE INDICATORS

In this section, the quantifying factors for participation in an LEM based on DLT determined from the survey analysis are used to evaluate how they can affect the performance indicators of an LEM based on the simulation analysis. The quantifying factors are analyzed on how they can affect the performance indicators of LEM are the willingness to pay more for renewable energy, interest in LEM and willingness to join an LEM pilot project, willingness to join LEM based on full DLT, and willingness to join LEM based on Hybrid DLT.

A. WILLINGNESS TO PAY MORE FOR RENEWABLE ENERGY

The willingness to pay more for renewable energy (WPMR) is the consumers'/prosumers' willingness to pay a certain premium to buy renewable energy generated by producers/prosumers within their community. The survey results show that up to 56.7% of the participants are willing to pay a premium to have their energy sourced from renewable energy production. Reference [38] showed that by considering consumers/prosumers WPMR in a check and curtail combined with highest-to-lowest and periodic double auction clearing mechanism (CC-H2L-PDA), the traded energy of an LEM will be increased by 36.4% compared to a standard periodic market clearing mechanism. In a check and curtail LEM clearing, the market checks unsatisfied bids and curtails them before initiating another market clearing [38]. Furthermore, considering WPMR in a CC-H2L-PDA increases the trade price of the LEM by 12.0%. This paper will assume that these results are suitable to be used in our model since it was studied in a German case scenario and this data will be used to formulate the effect of willingness to pay a premium on the different performance indicators of the simulation analysis.

1) SELF-SUFFICIENCY AND SELF-CONSUMPTION RATIO

The market self-sufficiency (SS) and self-consumption (SC) ratios have similar characteristics at constant PtC ratio and will have similar effect on increasing the energy traded. In a community where 56.7% of the LEM participants are willing to pay a premium to buy renewable generated energy as received from the survey, and considering the result of the effect (36.4% increase) of WPMR on the traded energy quantity already established in literature [38], the overall increase in SS and SC due to WPMR will be around 20% at constant PtC ratio.

2) SHARE OF MARKET SAVINGS

The share of market savings (SMS) is already established as the resultant savings of the market participants in an LEM compared to when there is no LEM. In a market where consumers are willing to pay more for the same amount of electricity if it is coming from renewables, the resultant effect will not change the SMS of the LEM. This is because, the premium that is paid by the consumers is received by the prosumers without changing the market savings. Hence, WPMR has no effect on the SMS of the LEM at a constant PtC ratio.

3) SHARE OF INDIVIDUAL SAVINGS - CONSUMERS

An increase in the average trade price of LEM at constant PtC ratio decreases the average consumer savings. The consumer's share of individual savings (SIS) is proportional to the average consumer savings, increasing the LEM average trade price decreases the consumers SIS. By considering the effect of WPMR on the LEM trade price, we derive the equations shown in Appendix B to show the effect of WPMR on the consumers SIS. Hence, by considering the consumers WPMR, the consumers' SIS reduces according to Eq. (10).

4) SHARE OF INDIVIDUAL SAVINGS - PROSUMERS

An increase in the average trade price of LEM at a constant PtC ratio increases the average prosumer savings. The prosumer's share of individual savings (SIS) is proportional to the average prosumer savings, increasing the LEM average trade price increase the prosumers SIS. The equations derived in Appendix B show the effect of WPMR on the prosumers SIS. Hence, by considering the consumers WPMR, the prosumers SIS increases according to Eq. (12).

B. INTEREST IN LEM AND WILLINGNESS TO JOIN LEM PILOT PROJECT

The survey results show that only 28.1% of the participants are interested to join an LEM pilot project. This shows that in the current maturity of LEM added with limited awareness to local consumers, it is difficult to form an LEM of large community at the start of an LEM pilot project. Therefore, it is difficult to start a medium or large LEM community at the current stage of LEM. With a high percentage of responders willing to join in the future, the optimal values of an LEM performance indicators obtained from the simulation results can only be witnessed after some years from now. In summary, all the simulation performance indicators are affected equally by the willingness to join LEM pilot project. However, while values of performance indicators are zero at the start of pilot projects for the medium and large communities, it is expected that after some years from now, the full results obtained from the simulations can be achieved for all the community types.

C. WILLINGNESS TO JOIN LEM BASED ON FULL DLT

Developing LEM based on a full DLT features require development of a platform for trading local energy that has the capability to offer all the features of DLT including using cryptocurrency for the payment of traded energy. LEM participants are required to be completely involved in such market to make it a viable one because they need to be able to manage their cryptocurrency by themselves. From the results of the survey (Figs. 6 and 7), while 31 % of the participants are neutral to utilizing LEM with full DLT features, 33 % will not like to participate in such a market. If applied to the community simulation, it means that not all members of the community will be willing to participate in such a market thereby reducing the performance of such a market. Hence, with the current survey results, we conclude it that with the current maturity stage of DLT, if a fully DLT based LEM is implemented, that all LEM performance indicators will reduce by at least 42 % compared to the expected results from the community simulation.

D. WILLINGNESS TO JOIN LEM BASED ON HYBRID DLT

LEM based on hybrid DLT is an LEM that combines selected DLT features to implement a trading platform for consumers and prosumers. The survey results of Fig. 7b shows that most participants are interested in having selected features of DLT such as trust and transparency in their LEM platform. Hence, this will affect the level of participation in such market if implemented and finally, increase the performance indicator of such a market compared to an LEM based on a full DLT features. The expected out come of Fig. 7b is that an LEM based on hybrid DLT features will only reduce the expected value of all the LEM performance indicators by 17%.

E. COMBINED QUANTIFYING FACTORS

The identified quantifying factors are combined in two different ways to evaluate the resultant effect on the LEM performance indicators. The first scenario is the start of a pilot project of an LEM based on full DLT where prosumers and consumers are willing to pay premium for renewable energy (SPP+LEMDLT+WPMR). The second scenario is 5 years after the start of a pilot project of an LEM based on hybrid DLT where prosumers and consumers are willing to pay premium for renewable energy (FASPP+LEMHDLTT+WPMR). The effect of the combined quantifying factors on the performance indicators is the resultant effect based on the combined factors.

Table 5 displays the summary of the effects of the quantifying factors on the performance indicators for selected communities (Comm.) of the simulation results, PtC and nPP ratios equal to 0.8 and 0.4, respectively. In Table 5, value means the original results determined from the simulation for the performance indicator. Other columns show the value of the performance indicator when the prosumers are willing to pay more for renewable energy (WPMR), at the start of a pilot project (SPP), five years after start of a pilot project (FASPP), for LEM fully based on DLT (LEMDLT), for LEM based on hybrid DLT (LEMHDLT), SPP+LEMDLT+WPMR scenario (Comb.1) and FASPP+LEMHDLTT+WPMR scenario (Comb.2). The complete results and input data are explained in details and made open source which is accessible from [39]. The best performance for all indicators is witnessed at the Comb.2 scenario. The maximum SS for data shown in Table 5 is 44.7% witnessed in community E. In the same way, the maximum SC and SMS are 66.9% and 36.1% resulting from communities B and D, respectively.

V. CONCLUSION

This paper presents an analysis of the quantifying factors for participation in a blockchain-based LEM. The methods used

TABLE 5. SS, SC and SMS for different LEM quantifying factors and varying community sizes with PtC ratio = 0.8 and nPP ratio = 0.4.

S/N	Comm.	Value [%]	WPMR [%]	SPP [%]	FASPP [%]	LEMDLT [%]	LEMHDLT[%]	Comb.1 [%]	Comb.2 [%]
SS									
1	A	42.7	51.5	–	42.7	24.7	35.4	–	42.2
2	B	43.7	52.6	–	43.6	25.3	36.2	–	43.2
3	C	43.0	51.2	–	43.0	35.7	35.4	–	42.5
4	D	42.0	50.6	41.8	41.7	24.3	34.8	32.7	41.5
5	E	45.2	54.5	45.2	45.2	26.2	37.5	35.3	44.7
6	F	43.1	52.0	43.1	43.1	25.0	35.7	33.6	42.7
SC									
1	A	53.4	63.3	–	53.4	31.0	44.3	–	51.9
2	B	68.9	81.6	–	68.9	39.9	57.1	–	66.9
3	C	54.2	64.3	–	54.2	31.4	45.1	–	52.7
4	D	45.5	53.9	45.5	45.5	26.3	37.7	35.5	44.2
5	E	64.5	76.5	64.5	64.5	37.4	53.5	50.3	62.7
6	F	61.1	72.4	61.1	61.1	35.4	50.7	47.7	59.4
SMS									
1	A	24.5	24.5	–	24.5	14.2	20.3	–	20.1
2	B	24.6	24.6	–	24.6	14.2	20.4	–	20.1
3	C	42.6	42.6	–	42.6	24.7	35.4	–	34.9
4	D	44.0	44.0	44.0	44.0	25.5	36.5	34.3	36.1
5	E	41.9	41.9	41.9	41.9	24.3	34.7	32.6	34.3
6	F	40.6	40.6	40.6	40.6	23.5	33.7	31.7	33.3

in this work were a survey analysis which was distributed online among household consumers and prosumers, and a community-based simulation of single layer LEM model with varying community sizes and prosumers to consumers ratios. The survey received a total of 261 responses and the results analysis show that consumers and prosumers are more interested in security of their supply, followed by economic value that may arise from their consumption/supply before ecological benefits. Also, the major reason for most consumers and prosumers to participate in an LEM is to promote renewable energy and the consumers/prosumers are willing to pay more for renewable energy supply. While majority of prosumers/consumers are willing to join LEM, most of them are only willing to join pilot projects in the future. This shows that most prosumers/consumers still do not trust new technology. Also, the major blockchain features that can drive local electricity traders (LETs) into LEM are trust and transparency. The community-based simulation analysis showed that varying the annual production to consumption ratio has more effect on the economic and technical benefits of LEM compared to varying number of prosumers to total participants (nPP) ratios. Also, medium and small communities with nPP ratio between 0.3 to 0.5 create more economic and technical benefits to LETs compared to large communities.

Finally, modelling the quantifying factors for participating in a blockchain-based LEM with the community-based simulation results show that an optimal LEM based on DLT can be achieved in the future in a community scenario where the participants are willing to pay more to consume local renewable generated electricity and with a hybrid blockchain-based LEM. In future work, a hybrid blockchain-based local energy market framework will be developed based on the identified blockchain features that attract consumers and prosumers to trade in a blokchain based LEM such as transparency and trust. Our model will be further extended to use intelligent agents to determine the behaviours of the LEM performance indicators outside the simulation range based on the input and the results of the simulation.

APPENDIX A
SURVEY QUESTIONS AND SCREEN SHOOT

A. SURVEY QUESTIONS

1) ENVIRONMENTAL PROTECTION/ ENERGY

1. Where do you see yourself in this triangle? Please evaluate the answers with a scale from 1-5 from the less important to the most important aspect?

a. Security
b. Economy
c. Ecology
Remark:
1-not important,
2-less important
3-neutral
4-important
5-very important

2. Will you pay more for your electricity consumption only to increase the usage of RES?

a. Yes
b. Maybe in the future
c. No 3. Please evaluate the answers with a scale from 1-5 from the less important to the most important aspect? Would you prefer that the energy you consume is generated by:

a. Sustainable
b. Non-sustainable
c. Not-interested
Remark:
1-not important
2-less important
3-neutral

4-important
5-very important

2) LOCAL ENERGY MARKET

*Video explanation of LEM (LO3 Energy Presents Allgäu Microgrid at AÜW (Deutsch) - YouTube) https://www.youtube.com/watch?v = dPhfKGQEdxY

1. During the time that your PV system is producing surplus, would you sign up to participate by trading the surplus energy in a local energy market?
a. I am part of LEM
b. Yes, very interested
c. Neutral
d. Not interested

2. Where do you/ would you prefer to share or trade your energy?
a. Direct neighbors
b. Block/suburb
c. Village/city
d. It doesn't matter
e. Other

3. Would you participate in LEM if you could:
a. Promote renewable energy systems
b. Part of Energy share Community
c. monetary winning from energy trading
d. I don't want to participate
e. Other reasons

4. Would you be interested in joining a pilot community project?
a. Yes
b. No c. Maybe in the future

3) ROLE OF TECHNOLOGY IN ENERGY SECTOR

1. How important is it for you to know in real time your load consumption and/or production?
a. Very important
b. Important
c. Neutral
d. Less important
e. Not important

2. I trust the energy-apps, smart meter and intelligent batteries?
a. Strongly disagree
b. Disagree
c. Neutral
d. Agree
e. Strongly agree

4) FUTURE ENERGY

According to (https://www.ewl.wiwi.uni-due.de/forschung /forschungsprojekte-ewl/esys-energiesysteme-der-zukunft/) This is what the future could look like in 2050: Generating electricity primarily from wind and sun. Cars fill up with electricity or hydrogen. Due to the increasing use of renewable energies, electricity is no longer produced in large power plants, but also in smaller generation units. Private individuals and companies feed electricity into the grid with their own systems. The citizens see the development as an opportunity to actively help the energy transition.

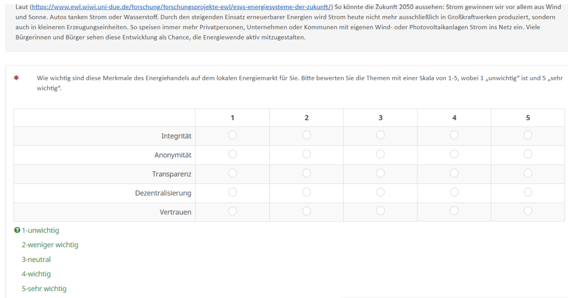


FIGURE 13. A Part of survey question displayed on SurveyMonkey website.

1. Are you willing to use an alternative way of paying or to be paid for energy trading?
a. Strongly agree
b. Agree
c. Neutral
d. Disagree
e. Strongly disagree

Alternative- Coupons, Vouchers. For a better understanding check this video: How It Works | GrassrootsEconomics

2. How important are these features of energy trading in local energy market for you:
1-not important
2-less important
3-neutral
4-important
5-very important
immutability 1 2 3 4 5
anonymity 1 2 3 4 5
transparency 1 2 3 4 5
decentralization 1 2 3 4 5
trust 1 2 3 4 5

5) GENERAL QUESTIONS

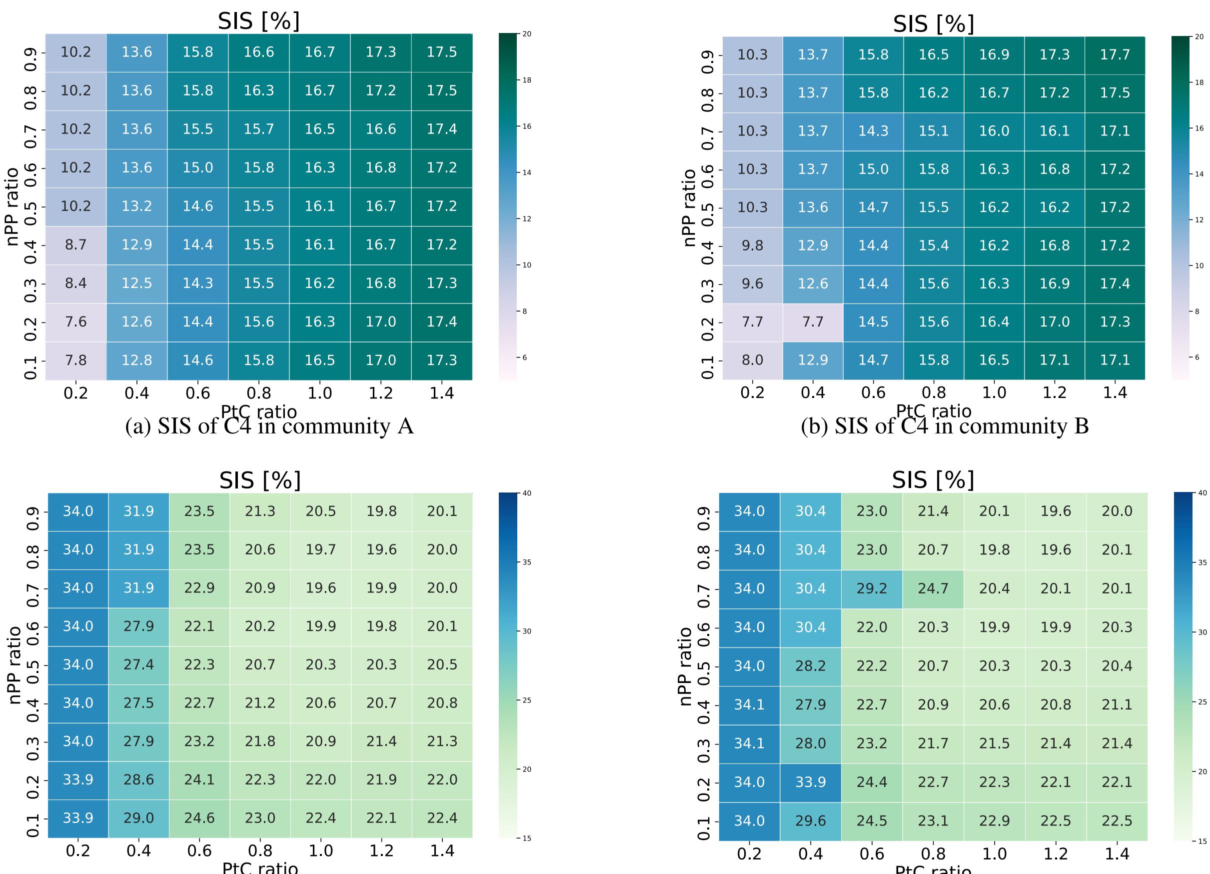
1. What's your age?
a. Below 30
b. 30- 55
c. Above 55

2. The yearly net incomes:
a. Below 35.000 €
b. 35.000-50.000 €
c. Above 50.000 €

3. Where do you live?:
a. Rented house/ apartment
b. Own house
c. Other

4. Are you aware of your monthly consumption?

5. Which operator or energy trader would you prefer to get your energy from?
a. Local council
b. Local community energy group
c. Energy supplier/ retailer



(a) SIS of C4 in community A
(b) SIS of C4 in community B
(c) SIS of P5 in community A
(d) SIS of P5 in community B

FIGURE 14. Economic indicators for varying PtC and nPP ratio in large communities.

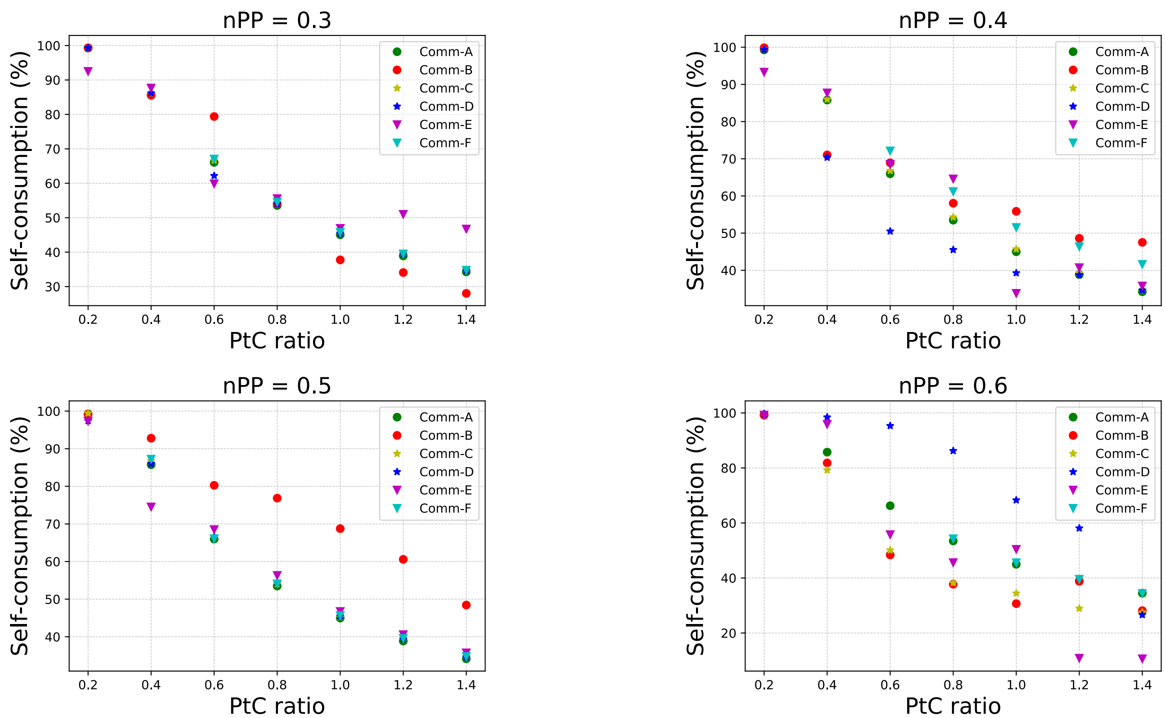


FIGURE 15. Community self-consumption ratio for varying PtC and nPP ratio, and community sizes.

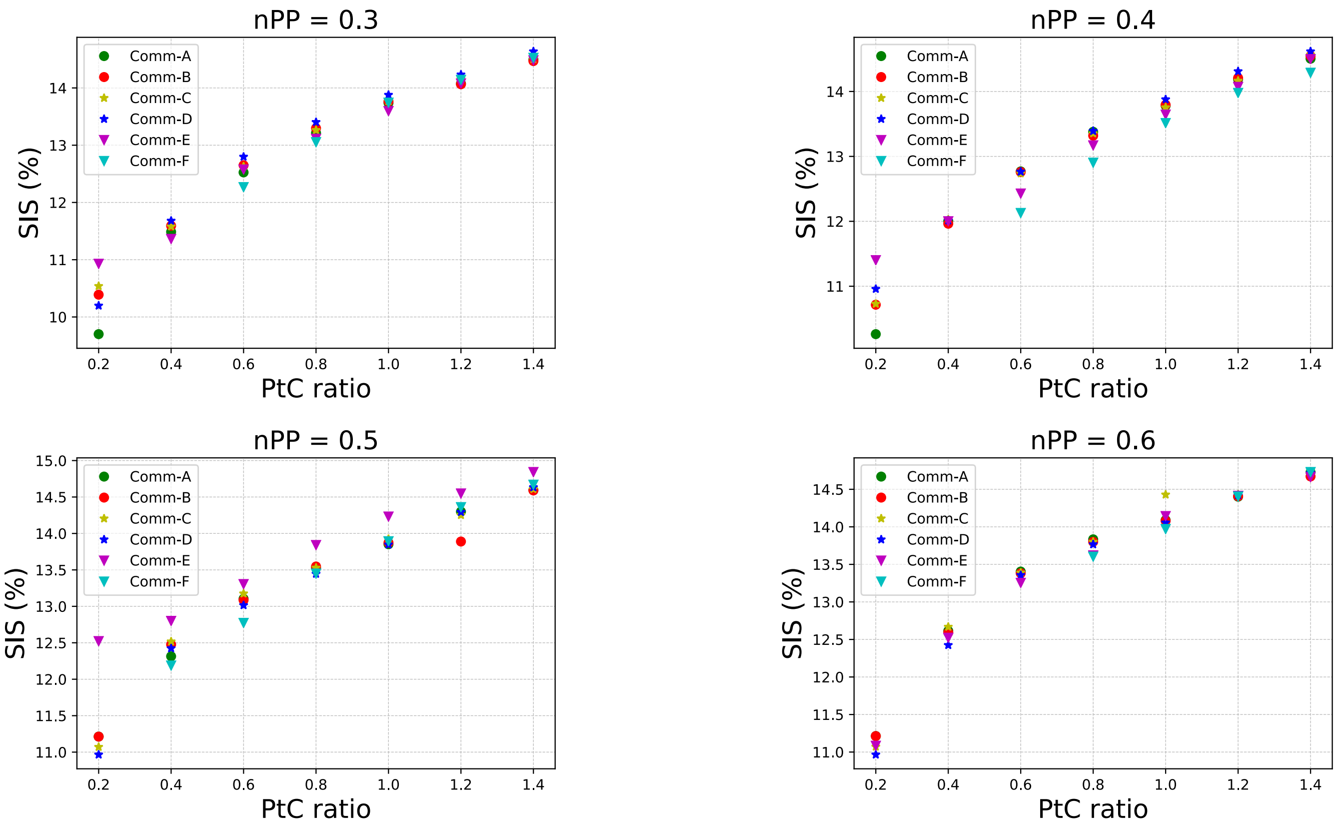


FIGURE 16. **C1 SIS for varying PtC and nPP ratio, and community sizes.**

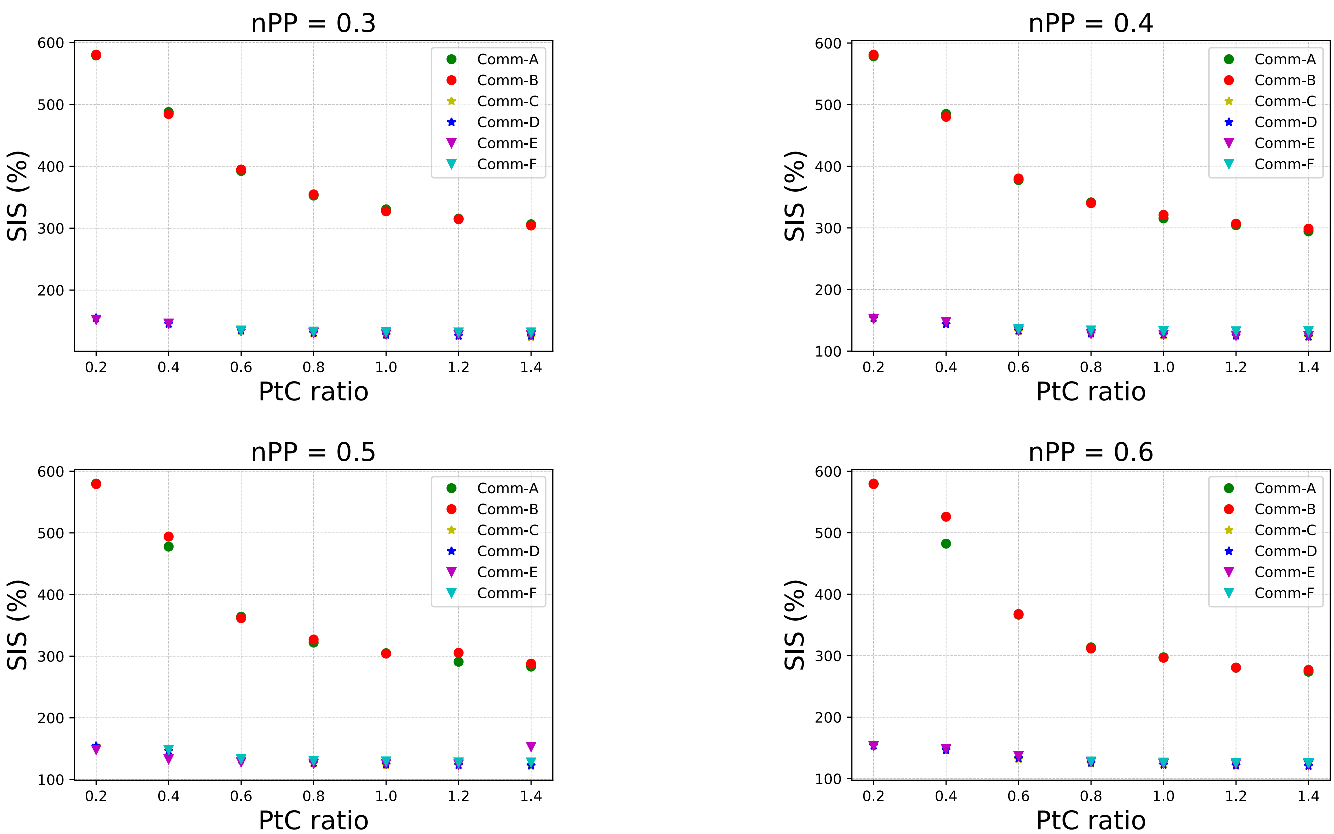


FIGURE 17. **P1 SIS for varying PtC and nPP ratio, and community sizes.**

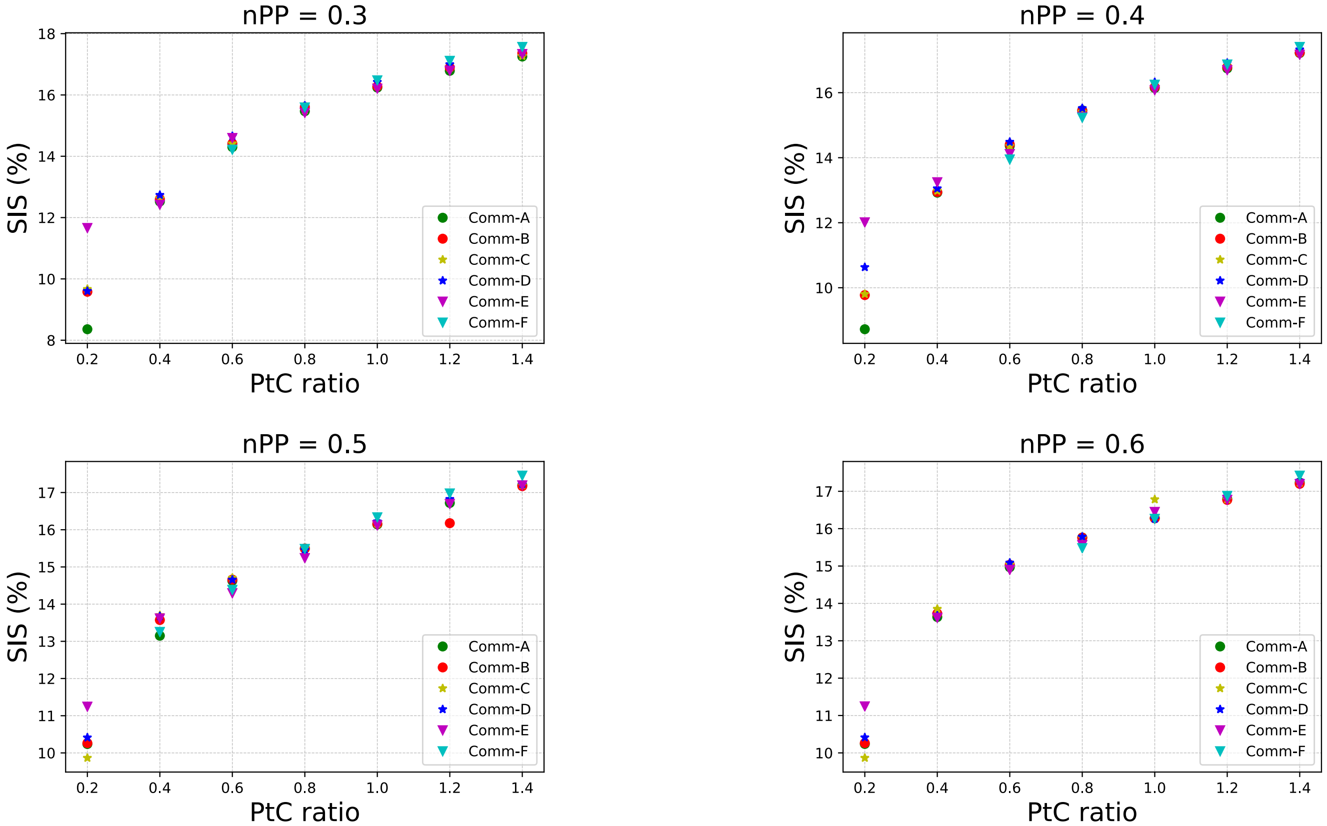


FIGURE 18. C4 SIS for varying PtC and nPP ratio, and community sizes.

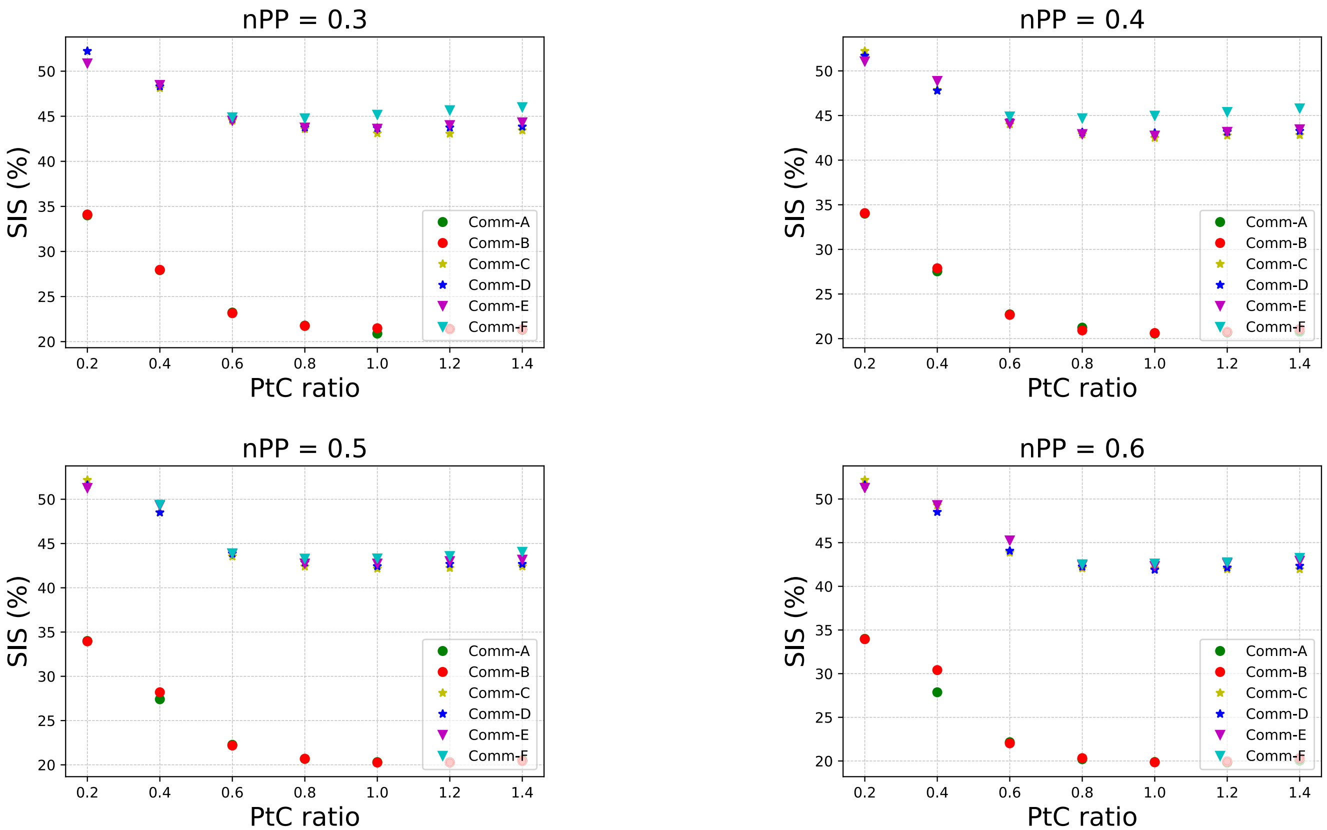


FIGURE 19. P5 SIS for varying PtC and nPP ratio, and community sizes.

B. SCREEN SHOOT OF PART OF SURVEY QUESTION DISPLAYED ONLINE

Fig. 13.

APPENDIX B
DERIVED EQUATIONS FOR DETERMINING THE SIS

$$\gamma = \frac{r_{wpmr} - r_{pda}}{r_{pda}} \tag{8}$$

$$SIS_{b,pda} \approx \frac{p_g - r_{wpmr}}{p_g} \tag{9}$$

$$SIS_{b,wpmr} \approx \frac{r_{wpmr}}{r_{pda}} SIS_{s,pda} - \gamma \times \beta \tag{10}$$

$$SIS_{s,pda} \approx \frac{r_{wpmr} - p_{fit}}{p_{fit}} \tag{11}$$

$$SIS_{s,wpmr} \approx \frac{r_{wpmr}}{r_{pda}} SIS_{s,pda} + \gamma \times \beta \tag{12}$$

NOMENCLATURE

β	Percentage of LEM participants from the survey willing to pay premium to buy more renewable energy.
γ	Weighted average ratio of increase in trade price for a market with WPMR compared to standard PDA.
p_{fit}	Electricity sell price to grid in kWh.
p_g	Electricity buy price from grid in kWh.
r_{pda}	Average trade price for a standard PDA market.
r_{wpmr}	Average trade price for WPMR market.
$SIS_{b,pda}$	Consumers SIS in a standard PDA market.
$SIS_{b,wpmr}$	Consumers SIS in a market that permits WPMR.
$SIS_{s,pda}$	Prosumers SIS in a standard PDA market.
$SIS_{s,wpmr}$	Prosumers SIS in a market that permits WPMR.

APPENDIX C
FURTHER SIMULATION BASED ANALYSIS RESULTS

See Figures 14, 15, 16, 17, 18, and 19.

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GODWIN C. OKWUIBE (Member, IEEE) received the B.Eng. degree in electrical engineering from the University of Nigeria, Nsukka, Nigeria, in 2013, and the M.Sc. degree in power engineering from the Technical University of Munich, Munich, Germany, in 2019, where he is currently pursuing the Ph.D. degree. He is currently a Researcher with OLI Systems GmbH, Stuttgart, Germany. His research interests include energy markets, game theory, the integration of renewable energy to the power grid, distributed generation, and the application of blockchain technology to energy markets.

THOMAS BRENNER received the M.Sc. degree in interdisciplinary sciences from ETH Zurich, Switzerland, and the Ph.D. degree from Cambridge University, U.K., with a thesis on the physics of polymer solar cells. He was the Head of the Junior Research Group "Hybrid Optoelectronics," University of Potsdam, Germany, until he moved to Dr. Langniß–Energie & Analyse, as a Senior Consultant, in 2015. He was responsible for the European Smart Grid Project "CALLIA" and was actively involved in the SINTEG Project "C/sells." At OLI Systems, he is responsible for the interface between the energy sector on one hand and the design and development of hardware and software on the other.

PETER TZSCHEUTSCHLER received the Diploma degree in electrical engineering and information technology from the Technical University of Munich (TUM), in 1998, and the Dr.-Ing. degree, in 2005. He joined the Chair of Energy Economy and Application Technology, TUM, as a Research Associate. He is currently working with the TUM Chair for Energy Economy and Application Technology. His research interests include decentralized and renewable energy systems with a special focus on building energy supply, cogeneration, energy management, and local energy markets.

THOMAS HAMACHER received the Ph.D. degree from the University of Hamburg, Hamburg, Germany, in 1994, for his work on baryonic beta decay after studying physics with the University of Bonn, Bonn, Germany; RWTH Aachen University, Aachen, Germany; and Columbia University, New York, NY, USA. In 2013, he was appointed as a Full Professor of renewable and sustainable energy systems with TUM. His research interests include energy and systems analysis, urban energy systems, the integration of renewable energy into the power grid, and innovative nuclear systems (including fusion). Other focuses of his work are the methods and fundamentals of energy models.