

# Cooperative Negawatt P2P Energy Trading for Low-voltage Distribution Networks

M. Imran Azim, Wayes Tushar, and Tapan K. Saha  
The University of Queensland, Brisbane, QLD 4072, Australia

## Abstract

In this paper, the formation and feasibility of negawatt (nW) peer-to-peer (P2P) energy trading in a grid-connected energy network are studied. In particular, a framework is presented to introduce nW P2P trading concept in the local electricity market in order to provide cost savings to each participating prosumer. To capture the decision-making strategy of various nW prosumers, a coalition game model is proposed whereby prosumers can trade energy frequently in a collaborative way. The proposed nW P2P trading framework satisfies the beneficial criterion of the coalition game. Also, it confirms the stability and prosumer-focused feature of the structured coalition. To distribute the total coalition payoff between nW prosumers, Shapley value and Nucleolus are used. Finally, simulation results are provided to examine the effectiveness of the developed nW P2P trading on an actual distribution network. The simulation results emphasise that the proposed nW P2P trading can 1) enable prosumers to minimise notable portion of their electricity costs compared to grid's-facilitated demand response scheme 2) keep total power loss and voltage profiles within permissible ranges, and 3) avoid network protection arrangements required for voltage regulation as opposed to kilowatt P2P trading.

## Index Terms

Negawatt peer-to-peer trading, coalition game model, electricity cost reduction, low-voltage distribution network, power loss, voltage profile

## NOMENCLATURE

### *Indices, Sets*

$t, \Delta t$	Index, length of each time slot,
$x$	Index of each prosumer,
$y, y_a, y_b$	Indices of distribution network nodes,
$\mathbb{R}$	Set of real numbers,
$2^{\mathcal{X}}$	Set of all possible coalitions,
$\mathcal{X}_p$	Set of all prosumers,
$\mathcal{X}, \mathcal{X}_s, \mathcal{X}_b$	Set of all nW P2P prosumers, sellers, buyers,
$\mathcal{Y}, \mathcal{E}$	Set of all distribution network nodes, branches,
$\mathcal{X}'_p, \mathcal{X}'_s, \mathcal{X}'_b$	Set of nodes of all prosumers, nW P2P prosumers, sellers, buyers

### Parameters

$\overline{w_x}$	maximum storage capacity of the battery,
$\eta$	Efficiency of the battery,
$\rho_x, -\rho_x$	Charging, discharging capacity of the battery,
$R_{y,y_a}, X_{y,y_a}, Z_{y,y_a}$	Resistance, reactance, impedance of the branch $(y, y_a)$ ,
$Y_{y_a}, G_{y_a}, B_{y_a}$	Admittance, conductance, susceptance of node $y_a$

### Variables

$P_{x,t}, P_{x,t}^b, P_{x,t}^f$	Total, base, flexible power demand of each prosumer $x$ at $t$ ,
$P_{x,t}^{pv}, P_{x,t}^{batt}$	Solar PV, battery power of each prosumer $x$ at $t$ ,
$P_{x,t}^{nt}, P_{x,t}^{df}$	Net demand, power deficiency of each prosumer $x$ at $t$ ,
$P_{x,t}^{or}$	Maximum power usage limit defined for each prosumer $x$ at $t$ ,
$P_{x,t}^{df-s}, P_{x,t}^{df-b}$	Power deficiency of each nW P2P seller, buyer at $t$ ,
$P_{x,t}^{fr}, P_{x,t}^{fi}$	Power decrease, increase by each seller, buyer for nW P2P trading at $t$ ,
$\overline{P_{x,t}^f}$	Maximum power increase limit for each nW P2P buyer at $t$ ,
$\omega_{x,t}^+, \omega_{x,t}^-$	SoC of the battery after charging, discharging,
$\lambda_t^{gr}, \lambda_t^{or}, \lambda_t^{nW}$	Higher, lower, nW P2P price in c/kWh at $t$ ,
$\lambda_t^{fr}$	Benefit in c/kWh offered by the grid to reduce demand at $t$ ,
$\pi_{x,t}^{nW}, \pi_{x,t}^{eq}$	Electricity cost with, without nW P2P trading at $t$ ,
$\tilde{\pi}_{x,t}$	Monetary reward provided by the nW P2P trading to each prosumer $x$ at $t$ ,
$I_{y,y_a}$	Current flow on the branch $(y, y_a)$ ,
$ V_m , \delta_m$	Voltage magnitude, voltage angle of each node $y$ ,
$S_y, P_y, Q_y$	Complex, active, reactive power of each node $y$ ,
$S_{y,y_a}, P_{y,y_a}, Q_{y,y_a}$	Complex, active, reactive power on the branch $(y, y_a)$ ,
$L_{y,y_a}$	Active power loss due to flow of power from node $y$ to $y_a$ ,
$L_t$	Total power loss in the network at $t$

### Vectors, Matrices, Coalitions

$\mathbf{p}_x^s, \mathbf{p}_x^b, \mathbf{p}_x^i, \mathbf{p}_x^r, \mathbf{p}_x^{bt}$	Column vector of $P_{x,t}^{df-s}, P_{x,t}^{df-b}, P_{x,t}^{fi}, P_{x,t}^{fr}, P_{x,t}^{bt}$ ,
$\omega_x^+, \omega_x^-, \lambda^n, \lambda^m$	Column vector of $\omega_{x,t}^+, \omega_{x,t}^-, \lambda_t^{nW}, \lambda_t^{or}$ ,
$\mathbf{P}^s, \mathbf{P}^b, \mathbf{P}^i, \mathbf{P}^r$	Matrix containing column vectors $\mathbf{p}_x^s, \mathbf{p}_x^b, \mathbf{p}_x^i, \mathbf{p}_x^r$ ,
$\mathbf{W}^+, \mathbf{W}^-, \mathbf{P}^{bt}$	Matrix containing column vectors $\omega_x^+, \omega_x^-, \mathbf{p}_x^{bt}$ ,
$\overline{\mathbf{W}}, \overline{\rho}, \overline{\mathbf{P}^f}$	Matrix containing vectors of $\overline{w_x}, \rho_x, \overline{P_{x,t}^f}$ ,
$\mathcal{L}$	Any coalition formed by the nW P2P prosumers,
$\Gamma(\mathcal{L}), \Pi(\mathcal{L})$	Decision variable set, total cost of coalition $\mathcal{L}$ ,

$\nu(\mathcal{L})$	Total benefit obtained by forming coalition $\mathcal{L}$ ,
$\mathcal{L}_d, \mathcal{L}_z$	Disjoint coalitions,
$\mathbf{h}$	Payoff vector of the coalition,
$\mathcal{O}$	Core of the coalition

## I. INTRODUCTION

The concept of negawatt (nW) management technique was first introduced in 1985 for efficient energy consumption [1]. The nW trading is defined as a trading mechanism, in which the electricity consumers can govern their energy consumption behaviour to facilitate the energy balance in a grid-tied network during shortage of energy supply [2]. Thus, nW trading can contribute towards stable operation of the electricity network in terms of adjusting energy imbalance [3]. Further, it can offer incentive-compatible revenues to the participating consumers if formulated in an coordinated fashion [4]. Please note that nW trading could be a part of flexible trading if it is formulated by imposing flexible rules so that the participants can reap maximum possible economic gains. Suppose two electricity consumers have 5 kWh of energy demand each. Assume Consumer B requires 2 kWh more energy. However, the grid can only supply 10 kWh in total to both of them. Assume Consumer A, Consumer B and the grid communicate to struck a trading deal. Consumer A is agreed to give up 2 kWh energy usage to help the Consumer B satisfy its needs. In this case, Consumer A acts as a nW seller. On the other hand, Consumer B functions as a nW buyer. Please note that demand response also deals with energy rescheduling activities. However, the rules and regulation of this mechanism is mostly managed by the grid with very limited inputs from the prosumers [2]. On the contrary, nW trading permits prosumers to trade with the grid or other prosumers in a prosumers-centric way through peer-to-peer platforms [5]. Thus, both selling and buying nW prosumers are expected to receive more monetary gains compared to the demand response. Nonetheless, due to the lack of advanced technologies, appropriate market mechanisms and policies, noticeable participation of the consumers, and well-grounded physical performance analysis, nW energy trading has remained mostly ineffective.

Recently, some proposals have been presented in light of technological developments to design grid-assisted nW energy trading [6] in supply-restricted circumstances in order to incentivise the participants in a convincing manner. In particular, a forecasting-driven hierarchical market structure is proposed in [7] with the purpose of avoiding energy imbalance through demand reduction of the agile consumers. Aggregator-based bidding strategies for nW trading are proposed in [8], [9] to minimise the supply-demand management cost. Energy management strategies via nW trading are also reported in [4], [10] to reward involving customers as there exists no direct monetary incentive mechanism at present to benefit the consumers opting for rescheduling their energy usage behaviour. Although these initial works have clearly paved the way to re-introduce nW trading in the 21<sup>st</sup> century, the direct intervention of the grid to set rules, regulations, and decisions has limited the inputs from engaging participants [2]. Consequently, the financial incentive obtained by each participant for demand reduction is not very attractive to motivate them to join in nW energy trading with the grid. For instance, it stays within 4 c/kWh in [4], [10]. Also, the energy buyers with larger demand do not benefit from this approach.

Few recent projects have also envisaged the prospects of nW energy trading in the future such as Yokohama Smart City project in Japan [11] and Demand Response Trial project in Australia [12]. However, the ultimate success of futuristic nW

trading projects will definitely lie in the prominent involvement of the end-users. Reluctance of energy consumers to adopt nW energy trading could see the failure of trial projects in reality in the same way it happened for kilowatt (kW) trading projects, Smart Trial [13] and FiT [14] for example. Therefore, there is a need to formulate a consumer-centric nW trading framework, whereby energy users (both who reduce their demand and require increased amount of demand) can maximise their energy cost savings during supply-restricted scenarios by executing bilateral transactions.

As such, prosumer-centric nW trading (without the direct involvement of the grid) via blockchain-empowered peer-to-peer (P2P) platform is discussed in [5], [15]. Please note that the nature of nW P2P trading characteristically differs from kW P2P trading in the context that there exists no exchange of energy surplus between prosumers (consumers who produce local power), rather prosumers adjust their demand in a P2P manner. Nevertheless, in [5], the nW P2P sellers (prosumers who can reduce their demand) trade with the nW P2P buyers (prosumers who are interested to purchase energy at reduced prices) in contrast with demand response strategy. Besides, nW P2P energy trading is also presented in [15] to settle the energy requirements between two prosumers by means of command-driven pricing procedure. Clearly, these studies have laid the foundation of prosumer-focused nW trading but can be extended further to establish nW P2P trading as a socially accepted framework.

Given this context, firstly, it is required to articulate how the concept of nW P2P energy trading can be brought into the distribution level to benefit household consumers. Secondly, an optimised nW P2P trading mechanism needs to develop to capture in-house demand management, trading flexibility, and electricity cost reduction aspects of the prosumers. Such formal framework can certainly permit prosumers to achieve their desired goals. On top of it, wide-scale participation of the prosumers in nW trading can be ensured to help distribution grid maintain the energy balance. Lastly, a detailed physical layer analysis of nW P2P trading is requisite. This is because any possible detrimental impact on the network could impede the successful deployment of nW P2P trading. In physical process, nW P2P trading is fundamentally contrasting to the kW P2P trading as there is no reverse power flow in the network caused by the excess energy export. However, frequent demand change resulted from the nW P2P trading could vary power losses and voltage profiles adversely. Hence, a comprehensive investigation is required to study the feasibility of a well-functioning nW P2P trading framework.

To this end, this paper stresses the importance of nW P2P trading in an energy network in order to facilitate the electricity usage of customers at cheaper rates. To achieve this objective, an optimised nW P2P trading mechanism is proposed using coalition game-theoretic model, whereby all rational participating prosumers make nW trading decisions cooperatively to reduce their electricity expenditures. The designed nW P2P coalition guarantees beneficial, stability and prosumer-centric properties. Further, Shapley value and Nucleolus are utilised to confirm unbiased distribution of the coalition payoff between nW prosumers. Finally, this paper conducts physical layer analysis of the developed nW P2P framework so that it can be deployed in practical distribution networks without violating the technical constraints. Particularly, the effects of nW P2P trading on the network losses and voltage profiles are compared with that of base network scenario. Also, a comparison is carried out between nW and kW P2P tradings so as to highlight the physical layer propriety of the nW P2P trading.

The major contributions of this paper can be summarised as follows:

- A process is demonstrated to adopt nW P2P trading at the distribution level to reduce the electricity costs of the prosumers.
- An optimised nW P2P energy trading framework is proposed to study the decision-making behaviour of different prosumers

using canonical coalition game (CCG)-theoretic model.

- An analytical demonstration is presented to validate the beneficial feature and stability of the proposed nW P2P coalition. Also, the prosumer-centric property and fair payoff allocation are confirmed.
- A feasibility study of the proposed framework is carried out on a real distribution network to inspect the physical performance in detail.

The reminder of the paper is structured as follows. The system models of the proposed work are described briefly in Section II. The next section presents the formation of the developed nW P2P trading mechanism by adopting the CCG framework. A number of simulation results are provided in Section IV to validate the proposed model. Lastly, the concluding remark is outlined in Section V.

## II. SYSTEM DESCRIPTIONS

The proposed system contains prosumers connected to a typical low-voltage (LV) distribution network. All prosumers are assumed to have a smart meter known as trans-active meter (TAM) [16]. TAM is a separate smart meter from the conventional energy meter that can 1) record the solar PV generation data, 2) record the internal demand, 3) determine the generation surplus and demand deficiency, 4) record the state-of-charge (SoC) of the battery, and 5) record the traded quantity and price [17]. Also, each prosumer is assumed to possess an account in a distributed communication platform, such as blockchain [18], which is linked with the TAM to receive signal regarding excess generation or load deficiency. Once the signal is obtained, a prosumer can start striking financial deals with other prosumers through blockchain platform in the virtual layer [19]. The energy surplus, deficiency, trading quantity and pricing data of a prosumer are essentially transferred from its TAM over the protected communication platform and based on these data information selling and buying orders are created [20]. A cooperative nW P2P market framework is then adopted to conduct nW trading between prosumers according to the selling and buying orders. Lastly, financial transactions are accomplished upon the efficacious matching of selling and buying orders and the contracted energy quantities are adjusted over the physical network [21]. A third party labelled as P2P market coordinator (PMC) is assumed to be responsible to maintain the distribution network under the policy of coordinated P2P market [21].

Fig. 1 illustrates prosumers make decisions related to their nW energy transactions virtually in order to reduce their energy costs without the intervention of the PMC. Now, the decisions are verified by the PMC through power flow analysis to demonstrate the technical compatibility. In case of no network violation, the intended nW transactions are labelled as safe for the network. Otherwise, a feedback is sent to the prosumers to rectify their preferred trading. The PMC can adopt centralised protection methods, such as network constraints management [22], coordinated voltage management [17], local voltage support [23], voltage-power control [24], and regulated trading framework [25] to settle safe nW P2P trading quantities.

### A. Prosumers' Model

Let  $x$  be index of each prosumer and  $\mathcal{X}_p$  be the set of all prosumers. It is assumed that each prosumer  $x \in \mathcal{X}_p$  is equipped with a rooftop solar photovoltaic (PV) system, a battery storage system and some typical flexible loads that include refrigerator, washing machine, dishwasher and air conditioner [26]. To meet the internal demand, prosumer  $x$  can use its PV generated

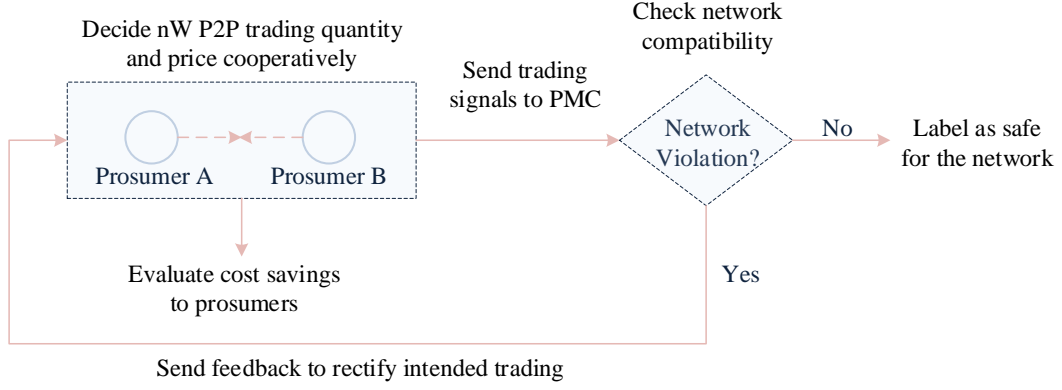


Fig. 1: This figure illustrates the coordinated nW P2P system model.

and/or battery stored power. Contrarily, it can sell excess power to the grid by means of feed-in-tariff (FiT) scheme after meeting own demand and charging the battery for future use.

Let  $P_{x,t}^b$  and  $P_{x,t}^f$  be the base and flexible power demand of prosumer  $x \in \mathcal{X}_p$  at any time  $t \in \mathcal{T}$ . The total power demand  $P_{x,t}$  of prosumer  $x$  is:

$$P_{x,t} = P_{x,t}^b + P_{x,t}^f, \quad \forall x \in \mathcal{X}_p, \forall t \in \mathcal{T} \quad (1)$$

Let solar PV power generation of prosumer  $x$  at time  $t$  be  $P_{x,t}^{pv}$ . Assume  $P_{x,t}^{batt}$  implies the battery power, which is positive during charging and negative during discharging.  $P_{x,t}^{batt}$  is bounded by maximum charging capacity  $\rho_x$  and minimum discharging capacity  $-\rho_x$  respectively. The charging and discharging operations of the battery are maintained by the SoC  $\omega_{x,t}$ , which is determined by the maximum storage capacity  $\bar{\omega}_x$ . The technical characteristics of the battery can be formulated as [27]:

$$\omega_{x,t}^+ = \omega_{x,t-1} + (\eta \times P_{x,t}^{batt} \times \Delta t), \quad \omega_{x,t}^- = \omega_{x,t-1} + \left( \frac{-P_{x,t}^{batt} \times \Delta t}{\eta} \right), \quad \forall x \in \mathcal{X}_p, \forall t \in \mathcal{T} \quad (2a)$$

$$0 \leq \omega_{x,t}^+ \leq \bar{\omega}_x, \quad -\bar{\omega}_x \leq \omega_{x,t}^- \leq 0, \quad \forall x \in \mathcal{X}_p, \forall t \in \mathcal{T} \quad (2b)$$

$$0 \leq P_{x,t}^{batt} \leq \rho_x, \quad \forall x \in \mathcal{X}_p, \forall t \in \mathcal{T} \quad (2c)$$

$$-\rho_x \leq -P_{x,t}^{batt} \leq 0, \quad \forall x \in \mathcal{X}_p, \forall t \in \mathcal{T} \quad (2d)$$

where  $\Delta t$  is the time length in hour and  $\eta$  represents the battery efficiency. Besides,  $\omega_{x,t}^+$  and  $\omega_{x,t}^-$  are SoC after charging and discharging the battery.

The net demand  $P_{x,t}^{nt}$  of each prosumer  $x \in \mathcal{X}_p$  at time  $t$  can be evaluated as follows:

$$P_{x,t}^{nt} = P_{x,t} - P_{x,t}^{pv} + P_{x,t}^{batt}, \quad \forall x \in \mathcal{X}_p, \forall t \in \mathcal{T} \quad (3)$$

If  $P_{x,t}^{nt} < 0$ , the prosumer  $x$  has excess generation. It is self-sufficient in case of  $P_{x,t}^{nt} = 0$ . On the other hand, it has to purchase power deficiency  $P_{x,t}^{df}$  from the electricity grid if  $P_{x,t}^{nt} > 0$ . That means, power deficiency refers to the positive value of the net demand, i.e.,  $P_{x,t}^{df} := P_{x,t}^{nt} > 0$ .

Assume an electricity supply-restricted circumstance, in which each prosumer purchases electricity at time-of-use (ToU)

prices but it needs to pay higher prices when its demand exceeds a pre-defined threshold [28]. Let each prosumer  $x$  be satisfied by the grid at the ToU price  $\lambda_t^{or}$  as long as its power deficiency  $P_{x,t}^{df}$  is not greater than the maximum usage limit  $P_{x,t}^{or}$ , i.e.,  $P_{x,t}^{df} \leq P_{x,t}^{or}$ , at time  $t$ . In case of  $P_{x,t}^{df} > P_{x,t}^{or}$ , prosumer  $x$  is required to purchase power from the electricity grid at a higher price  $\lambda_t^{gr}$  compared to  $\lambda_t^{or}$ , i.e.,  $\lambda_t^{gr} > \lambda_t^{or}$ . Now, the concept of nW P2P trading empowers each prosumer  $x$  to buy electricity from other prosumers in  $\mathcal{X}_p \setminus \{x\}$  if they decide to reduce their demand. Assume some prosumers are keen to participate in nW P2P trading to minimise their electricity bills. Let  $\mathcal{X} \subset \mathcal{X}_p$  be set of prosumers decided to engage in the nW P2P trading. Also, let  $\mathcal{X}_s$  and  $\mathcal{X}_b$  be the sets of nW P2P sellers and buyers respectively, where  $\mathcal{X}_s \cup \mathcal{X}_b = \mathcal{X}$  and  $\mathcal{X} \setminus (\mathcal{X}_s \cup \mathcal{X}_b) = \{\phi\}$ . Each nW P2P seller  $x \in \mathcal{X}_s$  has a power deficiency of  $P_{x,t}^{df} \leq P_{x,t}^{or}$  and reduces its demand by  $P_{x,t}^{fr}$ . On the other hand, each P2P buyer  $x \in \mathcal{X}_b$  possesses a power deficiency of  $P_{x,t}^{df} > P_{x,t}^{or}$  and purchases extra power of  $P_{x,t}^{fi}$  via nW trading. The power reduction and increase limit are bounded by  $P_{x,t}^{fr} \geq 0$  and  $P_{x,t}^{fi} \leq \overline{P_{x,t}^f}$  respectively.

The modified power deficiency of each nW P2P seller and each nW P2P buyer can be expressed as:

$$P_{x,t}^{df-s} = P_{x,t}^{df} - P_{x,t}^{fr}, \quad \forall x \in \mathcal{X}_s, \forall t \in \mathcal{T}, \quad \text{if } P_{x,t}^{df} \leq P_{x,t}^{or} \quad (4a)$$

$$P_{x,t}^{df-b} = P_{x,t}^{or} + P_{x,t}^{fi}, \quad \forall x \in \mathcal{X}_b, \forall t \in \mathcal{T}, \quad \text{if } P_{x,t}^{df} > P_{x,t}^{or} \quad (4b)$$

where  $P_{x,t}^{df-s}$  and  $P_{x,t}^{df-b}$  amounts of power are purchased by each seller and each buyer respectively at nW P2P trading slot  $t$ .

Each nW P2P seller  $x \in \mathcal{X}_s$  desires to maximise the difference between  $\lambda_t^{gr}$  and  $\lambda_t^{or}$  prices to earn greater revenue. On the contrary, the gap between  $\lambda_t^{gr}$  and  $\lambda_t^{or}$  prices is wished to be minimised by each nW P2P buyer  $x \in \mathcal{X}_b$  in order to decrease the expenditure substantially. Thus, this paper defines nW P2P trading price  $\lambda_t^{nW}$  as the middle value of  $\lambda_t^{gr} - \lambda_t^{or}$  to benefit both sellers and buyers.

$$\lambda_t^{nW} := \frac{\lambda_t^{gr} - \lambda_t^{or}}{2}, \quad \forall t \in \mathcal{T} \quad (5)$$

where nW P2P trading price  $\lambda_t^{nW}$  is defined in cents per kW hour (c/kWh).

Assume the buyer has to pay  $\lambda_t^{nW}$  to the contracted seller as its nW trading benefit to consume power from the network at price  $\lambda_t^{or}$ . Similar to other prosumers-instigated energy trading, for example, [29]–[31], it is assumed that a prosumer is permitted to act either as seller or buyer simultaneously in nW trading. As such, the electricity expense of prosumer  $x, \forall x \in \mathcal{X}$ , at time period  $t, \forall t \in \mathcal{T}$ , is:

$$\pi_{x,t}^{nW} = \left[ \left( P_{x,t}^{df-s} \times \Delta t \times \lambda_t^{or} \right) - \left( P_{x,t}^{fr} \times \Delta t \times \lambda_t^{nW} \right) \right] + \left[ \left( (P_{x,t}^{df-b} - P_{x,t}^{fi}) \times \Delta t \times \lambda_t^{or} \right) + \left( P_{x,t}^{fi} \times \Delta t \times (\lambda_t^{or} + \lambda_t^{nW}) \right) \right] \quad (6)$$

where the first term of (6) symbolises the electricity cost to each nW selling prosumer at time  $t$ . Whereas, the electricity expense of each nW buying prosumer is represented by the second term of (6).

Nevertheless, if an individual prosumer  $x, \forall x \in \mathcal{X}$ , wishes to trade the same amount of electricity solely with the grid, i.e., without engaging in the nW P2P trading, the equivalent electricity cost can be calculated as:

$$\pi_{x,t}^{eq} = \left[ \left( P_{x,t}^{df-s} \times \Delta t \times \lambda_t^{or} \right) - \left( P_{x,t}^{fr} \times \Delta t \times \lambda_t^{fr} \right) \right] + \left[ \left( (P_{x,t}^{df-b} - P_{x,t}^{fi}) \times \Delta t \times \lambda_t^{or} \right) + \left( P_{x,t}^{fi} \times \Delta t \times \lambda_t^{gr} \right) \right] \quad (7)$$

where  $\lambda_t^{fr}$  signifies the benefit offered by the grid to reduce the flexible demand at an electricity-constrained period.

The monetary reward to each prosumer  $x, \forall x \in \mathcal{X}$ , provided by the nW P2P trading is:

$$\tilde{\pi}_{x,t} = \pi_{x,t}^{eq} - \pi_{x,t}^{nW} = \left[ P_{x,t}^{fr} \times \Delta t \left( \lambda_t^{nW} - \lambda_t^{fr} \right) \right] + \left[ P_{x,t}^{fi} \times \Delta t \left( \lambda_t^{gr} - (\lambda_t^{or} + \lambda_t^{nW}) \right) \right] \quad (8)$$

Assume a toy example to demonstrate how both selling and buying prosumers can benefit via nW P2P trading. Suppose Prosumer A and Prosumer B have power demand of  $P_{A,t}^{df} = 4$  kW and  $P_{B,t}^{df} = 4$  kW at a time period  $t$  of an hour respectively, where maximum usage limits of Prosumer A and Prosumer B are  $P_{A,t}^{or} = 4$  kW and  $P_{B,t}^{or} = 4$  kW respectively. Prosumer B (nW buyer) contacts Prosumer A (nW seller) to purchase 3 kW power by performing nW P2P trading, where extra purchased power (more than the maximum usage limit) of Prosumer B is  $P_{B,t}^{fi} = 3$  kW and demand reduction of Prosumer A is  $P_{A,t}^{fr} = 3$  kW. The modified power deficiencies of Prosumer A and Prosumer B become  $P_{A,t}^{df-s} = 1$  kW and  $P_{B,t}^{df-b} = 7$  kW respectively. The electricity prices are: lower price  $\lambda_t^{or} = 25$  c/kWh [32], higher price  $\lambda_t^{gr} = 1.6 \times \lambda_t^{or}$  [28], nW price  $\lambda_t^{nW} = (\lambda_t^{gr} - \lambda_t^{or})/2$  and demand reduction benefit  $\lambda_t^{fr} = 4$  c/kWh [10]. According to (6), the electricity costs of Prosumer A and Prosumer B yield:  $\pi_{A,t}^{nW} = \text{€}2.5$  and  $\pi_{B,t}^{nW} = \text{€}197.5$  respectively.

On the other hand, these costs of Prosumer A and Prosumer B are:  $\pi_{A,t}^{eq} = \text{€}13$  and  $\pi_{B,t}^{eq} = \text{€}220$  respectively if grid's set demand response strategy is employed. Thus,  $\tilde{\pi}_{A,t} = \text{€}10.5$  and  $\tilde{\pi}_{B,t} = \text{€}22.5$ . Therefore, nW P2P trading can facilitate Prosumer A and Prosumer B to cut down their electricity costs by  $\text{€}10.5$  and  $\text{€}22.5$  respectively.

### B. Distribution Network Model

Consider a distribution network. Let the set of nodes of this LV network be denoted by  $\mathcal{Y} = \{1, 2, \dots, Y\}$ , where node  $1 \in \mathcal{Y}$  implies the distribution sub-station. Also, let  $\mathcal{E} = \{1, 2, \dots, E\}$  be the set of all branches connecting the nodes. A branch between node  $y \in \mathcal{Y}$  and node  $y_a \in \mathcal{Y}$  is represented by  $(y, y_a) \in \mathcal{E}$ . For each node  $y \in \mathcal{Y}$ , the complex power and voltage are defined as  $S_y = P_y + jQ_y$  and  $V_y = |V_y| e^{j\theta}$ , where  $P_y, Q_y \in \mathbb{R}$  indicate active and reactive power demand of node  $y$  respectively.

Suppose some nodes of this network contain prosumers. Let  $\mathcal{X}'_p$  be the set of prosumers' nodes such that  $\mathcal{X}'_p \subset \mathcal{Y} \setminus \{1\}$ . It is assumed that each prosumer's node accommodates one prosumer. Hence, the total number of prosumers' nodes  $|\mathcal{X}'_p|$  is equal to the total number of prosumers  $|\mathcal{X}_p|$ , i.e.,  $|\mathcal{X}'_p| = |\mathcal{X}_p|$  [20]. Similarly,  $|\mathcal{X}'| = |\mathcal{X}|$ , where  $\mathcal{X}' \subset \mathcal{X}'_p$  refers to the set of nW prosumers' nodes. A nW prosumer plays the role of a buyer and consumes the virtually decided power from its connected network node  $y, \forall y \in \mathcal{X}'_b \subset \mathcal{X}'$ , for a given time slot  $t$  if  $P_{y,t}^{df} > P_{y,t}^{or}$ . Whereas, a nW prosumer acts as a seller if  $P_{y,t}^{df} \leq P_{y,t}^{or}$  and reduces the contracted quantity from its respective node  $y, \forall y \in \mathcal{X}'_s \subset \mathcal{X}'$ . Sets  $\mathcal{X}'_s$  and  $\mathcal{X}'_b$  denote the sets of nodes of nW P2P sellers and buyers respectively.

Now, the complex power flow on the branch  $(y, y_a) \in \mathcal{E}$  is symbolised as  $S_{y,y_a} = P_{y,y_a} + jQ_{y,y_a}$ , where  $P_{y,y_a}, Q_{y,y_a} \in \mathbb{R}$  represent active and reactive power flow through the branch  $(y, y_a)$  respectively. The voltage difference between node  $y$  and node  $y_a$  can be expressed as:

$$V_y - V_{y_a} = Z_{y,y_a} I_{y,y_a}, \quad \forall (y, y_a) \in \mathcal{E} \quad (9)$$

where  $Z_{y,y_a} = R_{y,y_a} + jX_{y,y_a}$ . Here,  $R_{y,y_a}, X_{y,y_a} \in \mathbb{R}$  are resistance and reactance of the branch  $(y, y_a)$  respectively.



The branch current flow  $I_{y,y_a}$  is:

$$I_{y,y_a} = \left( \frac{S_{y,y_a}}{V_y} \right)^*, \quad \forall (y, y_a) \in \mathcal{E} \quad (10)$$

By substituting (10) in (9) and taking the magnitude squared,

$$|V_{y_a}|^2 = |V_y|^2 + |Z_{y,y_a}|^2 |I_{y,y_a}|^2 - (Z_{y,y_a} S_{y,y_a}^* + Z_{y,y_a}^* S_{y,y_a}) \quad (11)$$

The complex power balance at each node  $y_a, \forall y_a \in \mathcal{Y}$ , can be represented as:

$$S_{y_a} = \sum_{y_b: (y_a, y_b) \in \mathcal{E}} S_{y_a, y_b} - \sum_{y: (y, y_a) \in \mathcal{E}} (S_{y, y_a} - Z_{y, y_a} |I_{y, y_a}|^2) + Y_{y_a}^* |V_{y_a}|^2 \quad (12)$$

where admittance  $Y_{y_a} = G_{y_a} + jB_{y_a}$ . Here,  $G_{y_a}, B_{y_a} \in \mathbb{R}$  are conductance and susceptance of node  $y_a$  respectively.

Utilising (12) and (10) in terms of real variables, the distribution network branch flow model [33],  $\forall y_a \in \mathcal{Y}$  and  $\forall (y, y_a) \in \mathcal{E}$ , can be written as:

$$P_{y_a} = \sum_{(y_a, y_b) \in \mathcal{E}} P_{y_a, y_b} - \sum_{(y, y_a) \in \mathcal{E}} (P_{y, y_a} - R_{y, y_a} |I_{y, y_a}|^2) + G_{y_a} |V_{y_a}|^2 \quad (13a)$$

$$Q_{y_a} = \sum_{(y_a, y_b) \in \mathcal{E}} Q_{y_a, y_b} - \sum_{(y, y_a) \in \mathcal{E}} (Q_{y, y_a} - X_{y, y_a} |I_{y, y_a}|^2) + B_{y_a} |V_{y_a}|^2 \quad (13b)$$

$$|V_{y_a}|^2 = |V_y|^2 - 2(R_{y, y_a} P_{y, y_a} + X_{y, y_a} Q_{y, y_a}) + (R_{y, y_a}^2 + X_{y, y_a}^2) |I_{y, y_a}|^2 \quad (13c)$$

$$I_{y, y_a} = \frac{P_{y, y_a}^2 + Q_{y, y_a}^2}{|V_y|^2} \quad (13d)$$

The active power loss due to flow of power from node  $y$  to  $y_a$  is:

$$L_{y, y_a} = \left| \frac{V_y - V_{y_a}}{Z_{y, y_a}} \right|^2 \times \mathbb{R}(Z_{y, y_a}), \quad \forall y, y_a \in \mathcal{Y} \quad (14)$$

The total power loss in the network at any time instant  $t$  can be calculated as:

$$L_t = \sum_{y, y_a \in \mathcal{Y}} L_{y, y_a}, \quad \forall t \in \mathcal{T} \quad (15)$$

Assume a toy example to investigate the possible impact of nW P2P trading on power losses and node voltages at the distribution level. Fig. 2 exhibits a typical 0.4 kV distribution feeder whose sub-station is signified by the node 1. The detail descriptions of this network can be found in [20]. Suppose the active power demand of nodes 2 – 6 are  $\{1.9, 4, 3.5, 2.8, 4\}$  kW respectively at a given time  $t$ . Prosumers at nodes 3 and 6 are interested for nW P2P trading. In Base Scenario, there is no nW P2P trading and all the nodes are satisfied by the distribution sub-station. Based on the power flow results using MATPOWER [34], 0.2456 kW power loss is incurred in total to supply 16.2 kW power to the consumers' nodes. All the branch losses and node voltages are depicted in the first rows of Table I and Table II respectively.

In Scenario 1, it is assumed that Prosumer B at node 6 requires 7 kW power when  $P_{A,t}^{or} = P_{B,t}^{or} = 4$  kW. Thus, Prosumer B contracts Prosumer A located at node 3 to reduce 3 kW. Consequently, the active power demand at node 3 and node 6 are modified to 1 kW and 7 kW respectively. Now, the total power loss in the network, as illustrated in the second row of Table

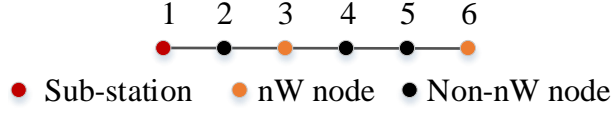


Fig. 2: This figure describes a typical LV distribution feeder.

I, increases to 0.2862 kW although the sub-station supplies the same amount of power, i.e., 16.2 kW, to the users' end. This is because 3 kW extra power travels to the far-end, i.e., node 6, of the network and incurs more losses through the feeder branches. Moreover, the second row of Table II reveals that the voltage at node 6 decreases from 0.9815 pu to 0.9792 pu due to increase of power demand. Nevertheless, the variations in power losses and voltage profiles are not prominent.

Scenario 2 is the opposite of Scenario 1, which demonstrates the consequence of nW P2P trading on the network if Prosumers A and B swap their physical locations. As is observed from the third rows of Table I and Table II, Scenario 2 lessens the total power loss to 0.2193 kW and enhances the voltage profile of node 6 to 0.9838 pu respectively owing to the fact of fewer amount of power flow to fulfill 1 kW power demand of node 6. Similar to Scenario 1, insignificant change in power losses and voltage profiles are also noticed in this scenario.

TABLE I: Power losses of the distribution feeder.

Scenario	$L_{1,2}$ (kW)	$L_{2,3}$ (kW)	$L_{3,4}$ (kW)	$L_{4,5}$ (kW)	$L_{5,6}$ (kW)	$L_t$ (kW)
Base Scenario	0.1545	0.0477	0.0270	0.0127	0.0036	0.2456
Scenario 1	0.1553	0.0480	0.0452	0.0266	0.0112	0.2862
Scenario 2	0.154	0.0475	0.0135	0.004	0.0002	0.2193

TABLE II: Voltage profiles of the distribution feeder.

Scenario	$V_2$ (pu)	$V_3$ (pu)	$V_4$ (pu)	$V_5$ (pu)	$V_6$ (pu)
Base Scenario	0.9902	0.9869	0.9843	0.9824	0.9815
Scenario 1	0.9902	0.9869	0.9835	0.9808	0.9792
Scenario 2	0.9902	0.9869	0.9851	0.9840	0.9838

### III. COALITION GAME-BASED PROPOSED TRADING FRAMEWORK

A coalition game essentially studies the strategic behaviour of various rational participants in a cooperative manner [35]. In order to design the proposed nW P2P trading framework under a canonical coalition game (CCG)-theoretic model, the energy profiles of all nW selling and buying prosumers are considered and a grand coalition  $\mathcal{X} = \mathcal{X}_s \cup \mathcal{X}_b$  is formed.  $X = |\mathcal{X}|$  represents the total number of prosumers in the grand coalition. This section presents the fundamental properties and algorithm of the proposed CCG-driven coalition. Also, it is explained how the developed CCG-based nW P2P trading constitutes itself as a prosumer-centric framework.

#### A. Coalition Fundamentals

Let  $\mathbf{p}_x^s, \mathbf{p}_x^b, \mathbf{p}_x^i, \mathbf{p}_x^r, \boldsymbol{\omega}_x^+, \boldsymbol{\omega}_x^-, \mathbf{p}_x^{bt}, \boldsymbol{\lambda}^n, \boldsymbol{\lambda}^m \in \mathbb{R}^T$  be the column vectors of  $P_{x,t}^{df-s}, P_{x,t}^{df-b}, P_{x,t}^{fi}, P_{x,t}^{fr}, \omega_{x,t}^+, \omega_{x,t}^-, P_{x,t}^{batt}, \lambda_t^{nW}, \lambda_t^{or}$  respectively, where column vectors are  $T$ -dimensional. Assume  $\mathbf{1}$  denotes a column vector of ones and following matrices are constructed:

$$\begin{aligned}
\mathbf{P}^s &\in \mathbb{R}^{X \times T} := [\mathbf{p}_1^s, \mathbf{p}_2^s, \dots, \mathbf{p}_X^s], & \mathbf{P}^b &\in \mathbb{R}^{X \times T} := [\mathbf{p}_1^b, \mathbf{p}_2^b, \dots, \mathbf{p}_X^b], & \mathbf{P}^i &\in \mathbb{R}^{X \times T} := [\mathbf{p}_1^i, \mathbf{p}_2^i, \dots, \mathbf{p}_X^i], \\
\mathbf{P}^r &\in \mathbb{R}^{X \times T} := [\mathbf{p}_1^r, \mathbf{p}_2^r, \dots, \mathbf{p}_X^r], & \mathbf{W}^+ &\in \mathbb{R}^{X \times T} := [\boldsymbol{\omega}_1^+, \boldsymbol{\omega}_2^+, \dots, \boldsymbol{\omega}_X^+], & \mathbf{W}^- &\in \mathbb{R}^{X \times T} := [\boldsymbol{\omega}_1^-, \boldsymbol{\omega}_2^-, \dots, \boldsymbol{\omega}_X^-], \\
\mathbf{P}^{bt} &\in \mathbb{R}^{X \times T} := [\mathbf{p}_1^{bt}, \mathbf{p}_2^{bt}, \dots, \mathbf{p}_X^{bt}], & \overline{\mathbf{W}} &\in \mathbb{R}^{X \times T} := [\overline{\boldsymbol{\omega}}_1 \mathbf{1}^T, \overline{\boldsymbol{\omega}}_2 \mathbf{1}^T, \dots, \overline{\boldsymbol{\omega}}_X \mathbf{1}^T], \\
\overline{\boldsymbol{\rho}} &\in \mathbb{R}^{X \times T} := [\boldsymbol{\rho}_1 \mathbf{1}^T, \boldsymbol{\rho}_2 \mathbf{1}^T, \dots, \boldsymbol{\rho}_X \mathbf{1}^T], & \overline{\mathbf{P}^f} &\in \mathbb{R}^{X \times T} := [\overline{\mathbf{p}}_1^f \mathbf{1}^T, \overline{\mathbf{p}}_2^f \mathbf{1}^T, \dots, \overline{\mathbf{p}}_X^f \mathbf{1}^T]
\end{aligned}$$

Now, the above matrices are defined for any coalition  $\mathcal{L} \subseteq \mathcal{X}$  as:  $\mathbf{P}^s(\mathcal{L})$ ,  $\mathbf{P}^b(\mathcal{L})$ ,  $\mathbf{P}^i(\mathcal{L})$ ,  $\mathbf{P}^r(\mathcal{L})$ ,  $\mathbf{W}^+(\mathcal{L})$ ,  $\mathbf{W}^-(\mathcal{L})$ ,  $\mathbf{P}^{bt}(\mathcal{L})$ ,  $\overline{\mathbf{W}}(\mathcal{L})$ ,  $\overline{\boldsymbol{\rho}}(\mathcal{L})$  and  $\overline{\mathbf{P}^f}(\mathcal{L})$ . The scaling and summation properties of the coalition are provided in Appendix I.

The decision variable set of coalition  $\mathcal{L}$  is defined as:

$$\Gamma(\mathcal{L}) := \{\mathbf{P}^s(\mathcal{L}), \mathbf{P}^b(\mathcal{L}), \mathbf{P}^i(\mathcal{L}), \mathbf{P}^r(\mathcal{L})\} \quad (16)$$

According to (6), the total electricity cost of coalition  $\mathcal{L}$  in each hour is expressed as:

$$\Pi(\mathcal{L}) = \Pi_{\mathcal{L}}(\Gamma(\mathcal{L})) = [(\boldsymbol{\lambda}^m)^\top (\mathbf{P}^s(\mathcal{L}) \mathbf{1} + \mathbf{P}^b(\mathcal{L}) \mathbf{1})] + [(\boldsymbol{\lambda}^n)^\top (\mathbf{P}^i(\mathcal{L}) \mathbf{1} - \mathbf{P}^r(\mathcal{L}) \mathbf{1})] \quad (17)$$

Further, the operational constraints of coalition  $\mathcal{L}$  can be written in the matrix form as:

$$\mathbf{P}^r(\mathcal{L}) \geq \mathbf{0}(\mathcal{L}), \quad \mathbf{P}^i(\mathcal{L}) \leq \overline{\mathbf{P}^f}(\mathcal{L}) \quad (18a)$$

$$\mathbf{0}(\mathcal{L}) \leq \mathbf{W}^+(\mathcal{L}) \leq \overline{\mathbf{W}}(\mathcal{L}), \quad -\overline{\mathbf{W}}(\mathcal{L}) \leq \mathbf{W}^-(\mathcal{L}) \leq \mathbf{0} \quad (18b)$$

$$\mathbf{0}(\mathcal{L}) \leq \mathbf{P}^{bt}(\mathcal{L}) \leq \overline{\boldsymbol{\rho}}(\mathcal{L}) \quad (18c)$$

$$-\overline{\boldsymbol{\rho}}(\mathcal{L}) \leq -\mathbf{P}^{bt}(\mathcal{L}) \leq \mathbf{0}(\mathcal{L}) \quad (18d)$$

where  $\mathbf{0}(\mathcal{L}) \in \mathbb{R}^{X \times T} := [\mathbf{0} \mathbf{1}_1(\mathcal{L}), \mathbf{0} \mathbf{1}_2(\mathcal{L}), \dots, \mathbf{0} \mathbf{1}_X(\mathcal{L})]$ . The column vector of zeros is indicated by  $\mathbf{0}$ .

### B. Coalition Value

The coalition value  $\nu$  refers to the numerical benefit that the involving prosumers receive as a cooperative group during the process of nW P2P trading. Let  $\nu(\mathcal{L}) : \mathbf{2}^{\mathcal{X}} \rightarrow \mathbb{R}$ , where  $\nu(\{\phi\}) = 0$  and  $\mathbf{2}^{\mathcal{X}}$  stands for the set of all coalitions, be the value function of any coalition  $\mathcal{L} \subseteq \mathcal{X}$ . In the proposed CGG with transferable utility,  $\nu(\mathcal{L})$  is defined as the difference between the summation of electricity costs for all prosumers who manage their energy individually  $\sum_{x \in \mathcal{L}} \sigma(\{x\})$  and the optimised coalition cost  $\sigma(\mathcal{L})$  during the execution nW P2P trading between prosumers.

$$\nu(\mathcal{L}) = \sum_{x \in \mathcal{L}} \sigma(\{x\}) - \sigma(\mathcal{L}) \quad (19)$$

where  $\sigma(\{x\}) = \pi_{x,t}^{eq}$  and  $\sigma(\mathcal{L})$  is defined as:

$$\begin{aligned}
\sigma(\mathcal{L}) &:= \min_{\Gamma(\mathcal{L}) \in \mathcal{F}(\mathcal{L})} \Pi_{\mathcal{L}}(\Gamma(\mathcal{L})) \\
\text{s.t. } & f(\Gamma(\mathcal{L}), \overline{\mathbf{P}^f}(\mathcal{L}), \overline{\mathbf{W}}(\mathcal{L}), \overline{\boldsymbol{\rho}}(\mathcal{L})) = 1
\end{aligned} \quad (20)$$

where  $f(\Gamma(\mathcal{L}), \overline{P^f}(\mathcal{L}), \overline{W}(\mathcal{L}), \overline{\rho}(\mathcal{L}))$  indicates an indicator function with respect to  $\Gamma(\mathcal{L})$  and the feasible set of  $\Gamma(\mathcal{L})$  is denoted by  $\mathcal{F}(\mathcal{L}) := \left\{ \Gamma(\mathcal{L}) \mid f(\Gamma(\mathcal{L}), \overline{P^f}(\mathcal{L}), \overline{W}(\mathcal{L}), \overline{\rho}(\mathcal{L})) = 1 \right\}$ .

Here, it is important to note that there is no guarantee that the nW P2P prosumers always form a stable grand coalition in CCG unless it is lucrative for them at all times compared to establishing disjoint coalitions or acting non-cooperatively. As such, the proposed nW P2P coalition should fulfill two basic properties of CCG, that include benefit of cooperation and stability of coalition [35], to validate itself as an effective framework.

### C. Beneficial Property

The beneficial property of CCG demonstrates that no subgroup of nW prosumers can gain benefit by abandoning the grand coalition. That means, the establishment of grand coalition, i.e., cooperation, is never disadvantageous for the nW P2P prosumers. This is related to the mathematical property of superadditive of the value function of the coalition game.

**Definition 1 (Superadditivity):** The value function  $\nu$  of a coalition game satisfies the mathematical property of superadditive if the sum of separate values of disjoint coalitions is not greater than the value of a union of all disjoint coalitions. Any two disjoint coalitions  $\mathcal{L}_d \in 2^{\mathcal{X}}$  and  $\mathcal{L}_z \in 2^{\mathcal{X}}$  cooperate together if the following inequality holds [36]:

$$\nu(\mathcal{L}_d \cup \mathcal{L}_z) \geq \nu(\mathcal{L}_d) + \nu(\mathcal{L}_z), \quad \forall \mathcal{L}_d \cap \mathcal{L}_z = \{\phi\} \quad (21)$$

**Theorem 1:** The value function of the proposed CCG, defined in (19), is superadditive. Thus, the P2P coalition formation is beneficial for the nW prosumers.

*Proof:* Please see Appendix II.

### D. Stability Property

The proposed nW P2P coalition payoff needs to be allocated between the participating prosumers in a stable manner such that no disjoint group of prosumers or individual prosumer receives any further incentive by leaving the grand coalition. The set of all feasible distributions of such payoff is defined as the core of the coalition [35].

**Definition 2 (Core):** Let  $\mathbf{h} \in \mathbb{R}^X$  be payoff vector, that satisfies the efficiency criterion and is feasible for the grand coalition if the grand coalition value  $\nu(\mathcal{X})$  is distributed completely to the  $X$  participants, i.e.,  $\sum_{x \in \mathcal{X}} h_x = \nu(\mathcal{X})$ . Further, a payoff vector  $\mathbf{h}$  is rational individually if every participant  $x$  can receive a benefit more than or equal to operating alone, i.e.,  $h_x \geq \nu(\{x\}), \forall x \in \mathcal{X}$ . Thus,  $\mathbf{h}$  can be labelled as an imputation and the core of the coalition is defined as [35]:

$$\mathcal{O} := \left\{ \mathbf{h} : \sum_{x \in \mathcal{X}} h_x = \nu(\mathcal{X}) \quad \text{and} \quad \sum_{x \in \mathcal{L}} h_x \geq \nu(\mathcal{L}), \quad \mathcal{L} \subseteq \mathcal{X} \right\} \quad (22)$$

If  $\mathcal{O}$  of the coalition game is non-empty, a feasible payoff allocation can be ascertained between all participating nW prosumers and hence, the coalition stability can be confirmed. The Bondareva-Shapley theorem, reliant on the balanced property, can be exploited to examine the non-emptiness of the core.

**Definition 3 (Balanced Game):** For a coalition  $\mathcal{L} \subseteq \mathcal{X}$ , a map  $\gamma(\mathcal{L}) \in [0, 1], \forall \mathcal{L} \in 2^{\mathcal{X}}$ , is a balanced collection of weights if  $\sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) \mathbf{1}_x(\mathcal{L}) = 1, \forall x \in \mathcal{X}$ .  $\mathbf{1}_x(\mathcal{L})$  represents the  $x^{\text{th}}$  element of vector  $\mathbf{1}(\mathcal{L}) \in \mathbb{R}^X$ . A coalition game is balanced, i.e., has non-empty core, if the following inequality holds [37]:

$$\sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) \nu(\mathcal{L}) \leq \nu(\mathcal{X}) \quad (23)$$

**Theorem 2:** The proposed CCG is balanced. Thus, the P2P coalition structure is stable for the nW prosumers.

*Proof:* Please see Appendix III.

#### E. Allocation of Payoff

Since the proposed CCG is balanced, the value function  $\nu$  of the proposed nW P2P coalition has a non-empty core. Thus, each prosumer involved in the nW trading should attain its payoff in an unbiased fashion. In this sub-section, Shapley value and Nucleolus are employed to distribute the coalition benefit fairly between the prosumers.

**Definition 4 (Shapley Value):** Shapley value remunerates each nW prosumer  $x \in \mathcal{X}$  pursuant to its marginal contribution to coalition  $\mathcal{L} \subseteq \mathcal{X}$ . The Shapley value  $\phi_x(\nu)$  of the coalition game assigned to each nW prosumer  $x$  is given by [38]:

$$\phi_x(\nu) = \sum_{\mathcal{L} \subseteq (\mathcal{X}) \setminus \{x\}} \frac{|\mathcal{L}|! (|\mathcal{X}| - |\mathcal{L}| - 1)!}{|\mathcal{X}|!} [\nu(\mathcal{L} \cup \{x\}) - \nu(\mathcal{L})] \quad (24)$$

where  $|\mathcal{L}|$  and  $|\mathcal{X}|$  indicate the number of nW prosumers in coalition  $\mathcal{L}$  and total number of nW prosumers in the grand coalition  $\mathcal{X}$  respectively. Besides, the marginal contribution of every nW prosumer  $x$  in coalition  $\mathcal{L}$  is represented by  $\nu(\mathcal{L} \cup \{x\}) - \nu(\mathcal{L})$ .

Once the total coalition value of the proposed nW P2P game is generated in (19), the allocated Shapley value to each nW prosumer can easily be computed in (24).

**Definition 5 (Nucleolus):** Let  $\ell(\mathbf{h}) \in \mathbb{R}^{2^X - 2}$  be a vector and the excesses of all coalitions, excluding the grand coalition  $\mathcal{X}$  and empty coalition  $\{\phi\}$ , are denoted by its entries. The entry arrangement follows the non-increasing sequence. The excess  $i(\mathcal{L}, \mathbf{h})$  quantifies the dissatisfaction level of the coalition  $\mathcal{L}$  with respect to the imputation  $\mathbf{h}$  and is defined as  $i(\mathcal{L}, \mathbf{h}) = \nu(\mathcal{L}) - \sum_{x \in \mathcal{L}} h_x$ . The Nucleolus  $\psi(\nu)$  is termed as the lexicographically minimal imputation, stable for balanced game, to reduce the dissatisfaction level of the participants such that [37]:

$$\ell_c(\psi(\nu)) \leq \ell_c(\mathbf{h}), \quad \forall \mathbf{h} \in \mathbb{R}^X, \forall c \in 2^X - 2 \quad (25)$$

The Nucleolus of the proposed CGG-enabled nW P2P coalition is found out by solving a sequence of linear programming (LP) problems in an iterative process described as follows:

- The objective function, formulated in (26a), is solved in Iteration 1 to minimise the largest excess for all coalitions by seeking through all possible imputations as expressed below:

$$\text{LP}_1 : i_1 = \min_{\mathbf{h}, i} i \quad (26a)$$

$$\text{s.t. } \sum_{x \in \mathcal{X}} h_x = \nu(\mathcal{X}), \quad \forall x \in \mathcal{X} \quad (26b)$$

$$\nu(\mathcal{L}) - \sum_{x \in \mathcal{L}} h_x \leq i, \quad \forall x \in \mathcal{L}, \quad \forall \mathcal{L} \notin \{\mathcal{X}, \{\phi\}\} \quad (26c)$$

where the efficiency criterion of  $\mathbf{h}$  is ensured by the constraint (26b), and  $i$  is specified as the largest excess for all possible coalitions by the constraint (26c).

Let  $i_1$  be the optimal solution of  $\text{LP}_1$ . Also, let  $\mathcal{I}_1$  be the set of coalitions corresponding to the constraint (26c) that is bidding or coalitions that are equal to all optimal solutions at  $i = i_1$ . The condition of Nucleolus to be in the core is  $i_1 \leq 0$ , where  $i_1$  symbolises the largest excess of the nucleolus.

- The following linear optimisation is solved in Iteration  $k$ , where  $k \geq 2$ , to obtain the unique optimal solution, i.e., Nucleolus, in the core.

$$\text{LP}_k : i_k = \min_{\mathbf{h}, i} i, \quad \forall k \geq 2 \quad (27a)$$

$$\text{s.t. } \sum_{x \in \mathcal{X}} h_x = \nu(\mathcal{X}), \quad \forall x \in \mathcal{X} \quad (27b)$$

$$\sum_{x \in \mathcal{L}} h_x = \nu(\mathcal{L}) - i_{k'}, \quad \forall x \in \mathcal{L}, \quad \forall \mathcal{L} \in \mathcal{I}_{k'}, \quad \forall k' \in [1, k-1] \quad (27c)$$

$$\nu(\mathcal{L}) - \sum_{x \in \mathcal{L}} h_x \leq i, \quad \forall x \in \mathcal{L}, \quad \forall \mathcal{L} \notin \{\mathcal{X}, \{\phi\}, \mathcal{I}_{k'}\}, \quad \forall k' \in [1, k-1] \quad (27d)$$

where constraint (27b) ascertains the efficiency criterion of  $\mathbf{h}$ , constraint (27c) finalises coalitions' excesses that have been bidding in previous iterations, and constraint (27d) fixes  $i$  as the largest excess for all spare coalitions in  $\text{LP}_k$ .

Besides,  $\mathcal{I}_{k'} := \{\mathcal{L} | \nu(\mathcal{L}) - \sum_{x \in \mathcal{L}} h_x = i_{k'}\}$  indicates the set of coalitions whose corresponding excesses are bidding according to (27d) in  $\text{LP}_{k'}$ .

#### F. Prosumer-centric Property

The success of the proposed CCG-empowered nW P2P trading framework definitely lies in the agile participation of the prosumers. Given this context, this sub-section outlines how the designed nW P2P mechanism fulfills the requirements to motivate prosumers to join in it and thus, can be entitled as prosumer-centric.

The motivation is closely connected with the psychological process that imitates real behaviour [36]. A number of motivational psychological models can be studied to capture the affinity of prosumers towards a certain behaviour. In this sub-section, rational-economic and positive reinforcement models are demonstrated in particular.

**Definition 6 (Rational-economic Model):** The rational-economic model prescribes that financially rational decisions influence people to adopt pro-environmental behaviour [39]. In other words, monetary benefit can be termed as a key motivator for rational prosumers to get themselves engaged in the nW P2P trading.

**Definition 7 (Positive Reinforcement Model):** The positive reinforcement establishes that a reinforcing stimulus influences a human response to a certain situation if same response guarantees positive outcomes during similar situations [40]. In other words, repeatedly confirmed benefit can motivate prosumers to have positive attitudes towards nW P2P trading.

In accordance with the aforementioned definitions, prosumers are very likely to accept nW P2P trading mechanism if it is structured complying with the rational-economic and positive reinforcement models. Thus, it is sufficient to demonstrate that the proposed nW P2P trading scheme abides by both the models to authenticate its prosumer-centric property.

The proposed nW P2P trading model complies with the rational-economic property because of the following facts:

- The coalition value of the developed nW P2P trading framework in (19) is defined with regard to the monetary benefit that the coalition offers for the participating prosumers.
- In Theorem 1, it is proven that none of the participating prosumers would gain better incentive by quitting the grand coalition. Hence, the constituted coalition is always beneficial for the prosumers.
- In Theorem 2, it is shown that the designed CCG is balanced, i.e., has non-empty core. Thus, the coalition stability is justified.
- Finally, the fairness in coalition value distribution between involving prosumers is ensured adopting Shapley value and Nucleolus.

Hence, all the engaging nW P2P prosumers in the proposed CCG framework are always content with the economic benefit reaped through cooperation.

Further, the nW P2P prosumers benefit financially every time they join in the proposed CGG-driven nW P2P trading mechanism as the stability and fairness of the formed coalition are always guaranteed. Clearly, this fulfills the criterion of the positive reinforcement model.

Consequently, it is reasonable to state that the proposed nW P2P trading is a prosumer-centric model.

#### G. Trading Algorithm

The algorithm to establish CCG-enabled nW P2P coalition is given in Algorithm 1. It provides the solution of the proposed nW P2P model when the buyer requires power greater than the maximum usage limit  $P_{x,t}^{or}$ , i.e.,  $P_{x,t}^{df} > P_{x,t}^{or}, \forall x \in \mathcal{X}_b \subset \mathcal{X}$ , and the seller possesses some sort of flexible demand  $P_{x,t}^{fr} \neq 0, P_{x,t}^{df} \leq P_{x,t}^{or}, \forall x \in \mathcal{X}_s \subset \mathcal{X}$  at a given time slot  $t$ . For any P2P coalition  $\mathcal{L} \subseteq \mathcal{X}$ , the optimal trading quantity of each prosumer in the coalition  $\mathcal{L}$  and c/kWh nW price of the coalition are decided satisfying operational constraints (18a)-(18d). The total coalition benefit is evaluated in (19), and then allocated between the participating nW prosumers using Shapley value and Nucleolus. Afterwards, each seller's demand  $P_{x,t}^{df-s}, \forall x \in \mathcal{X}_s$ , and each buyer's demand  $P_{x,t}^{df-b}, \forall x \in \mathcal{X}_b$ , during nW P2P trading are recorded in (4a) and (4b) respectively. Finally, a power flow study is performed by the PMC with the recorded demand  $P_{x,t}^{df-s}, \forall x \in \mathcal{X}_s$ , and  $P_{x,t}^{df-b}, \forall x \in \mathcal{X}_b$  to inspect the likely impact on the distribution network at which the nW participants are located. If there is no adverse effect on power losses and voltage profiles, the proposed CCG framework is approved by the PMC.

## IV. SIMULATION RESULTS

Some numerical results are presented in this section to articulate the efficacy of the proposed nW P2P trading framework in the distribution network. The considered scenarios and the purpose of those scenarios are depicted in Table III. Particularly, it is demonstrated that the developed nW P2P trading mechanism can 1) reduce the electricity cost to each participating prosumer

**Algorithm 1** Algorithm to form CCG-based nW P2P framework

---

```

1: for each trading slot  $t \in \mathcal{T}$  do
2:   if  $P_{x,t}^{df} > P_{x,t}^{or}, \forall x \in \mathcal{X}_b$ , and  $P_{x,t}^{fr} \neq 0, \forall x \in \mathcal{X}_s$  then
3:     Conduct nW P2P trading by forming CCG such that  $\mathcal{X}_s \cup \mathcal{X}_b = \mathcal{X}$ .
4:     for any nW P2P coalition  $\mathcal{L} \subseteq \mathcal{X}$  do
5:       Decide optimal trading quantity of each prosumer in the coalition  $\mathcal{L}$  and
       c/kWh nW price of the coalition satisfying operational constraints (18a)-(18d).
6:       Evaluate coalition benefit  $\nu(\mathcal{L})$  in (19).
7:       Distribute coalition benefit between the participating prosumers.
8:       Record each seller's demand  $P_{x,t}^{df-s}, \forall x \in \mathcal{X}_s$ , during nW trading in (4a).
9:       Record each buyer's demand  $P_{x,t}^{df-b}, \forall x \in \mathcal{X}_b$ , during nW trading in (4b).
10:      Perform power flow study with recorded  $P_{x,t}^{df-s}, \forall x \in \mathcal{X}_s$ , and  $P_{x,t}^{df-b}, \forall x \in \mathcal{X}_b$ .
11:      Compare the physical performance with the Base scenario.
12:      if No detrimental physical network is found by the PMC then
13:        Approve the proposed CCG.
14:      else
15:        Modify the intended trading amounts in the nW P2P coalition  $\mathcal{L}$ .
16:      end if
17:    end for
18:  else
19:    No nW P2P trading.
20:  end if
21: end for

```

---

compared to the demand response strategy [10], 2) keep power losses and voltage profiles within acceptable margins, and 3) perform better than kW P2P trading in terms of maintaining the regulation of network voltages.

TABLE III: Considered scenarios in the distribution network containing prosumers.

Scenario	Purpose
Electricity cost reduction of the prosumers	To evaluate how much electricity cost is saved by each participating prosumer compared to the demand response strategy.
Physical impacts on the distribution network	To investigate how nW P2P trading influences power losses and voltage profiles in comparison with Case the demand response strategy, and to label the safest type of P2P trading for the distribution networks.

Fig. 3 describes the single-line diagram of a 3 phase LV distribution network in Australia with 34 single-phase household customers' nodes (102 residential electricity consumers' nodes in total for 3 phases). Node 1 represents the distribution substation. Please see [41] for complete network descriptions. Nonetheless, the households located at nodes 5 – 14 of this network (30 customers in total) have rooftop solar PV systems and thus, can act as prosumers [25]. The solar PV systems have capacities ranging from 3 kW<sub>p</sub> to 6.6 kW<sub>p</sub> [42]. They are also assumed to have battery storage facilities ranging from 5 kWh to 10 kWh [43] and flexible loads such as refrigerator, washing machine, dishwasher and air conditioner [26]. The total power demand (with 5 minutes time step) and total locally generated solar PV (with 1 minute time step) for a typical day are displayed in Fig. 4a and Fig. 4b respectively. All household data (recorded in January 2018) are taken from a Brisbane-based research centre linked with The University of Queensland, Australia.

It is assumed that prosumers at nodes 5 – 10 are eager to take part in the proposed nW P2P trading framework, and the nW P2P coalition is established every 30 minutes apart. The nW selling prosumers are assumed to have enough flexible loads and the consent to sacrifice their comforts. The ToU prices are varied between 17 ¢/kWh and 35 ¢/kWh [32], whereas these prices



are 1.6 times more if electricity customers consume beyond the rated quantity [28]. The high and low FiT rates are set as 44 ¢/kWh and 10 ¢/kWh respectively [14]. Furthermore, the battery degradation cost and demand response benefit are considered as 4.2 ¢/kWh [44] and 4 ¢/kWh [10] respectively.

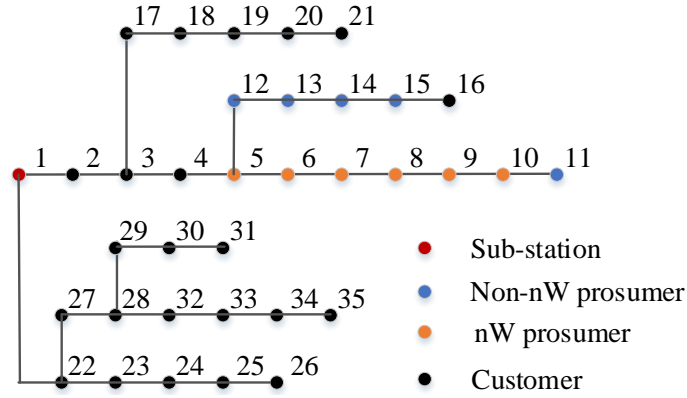
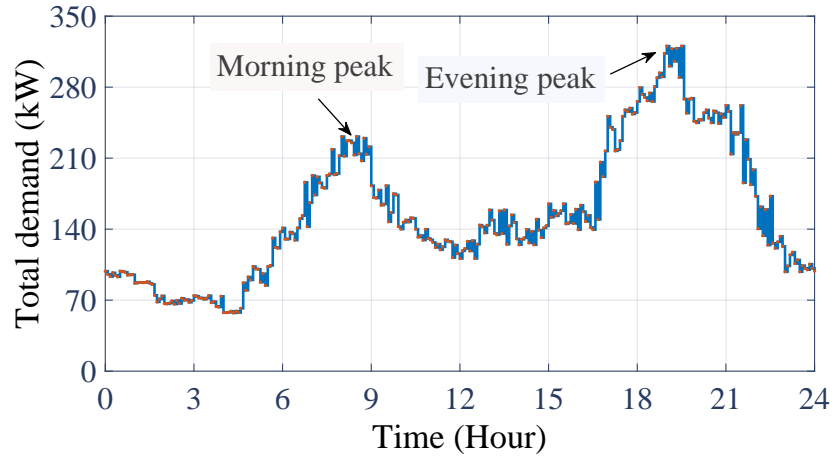
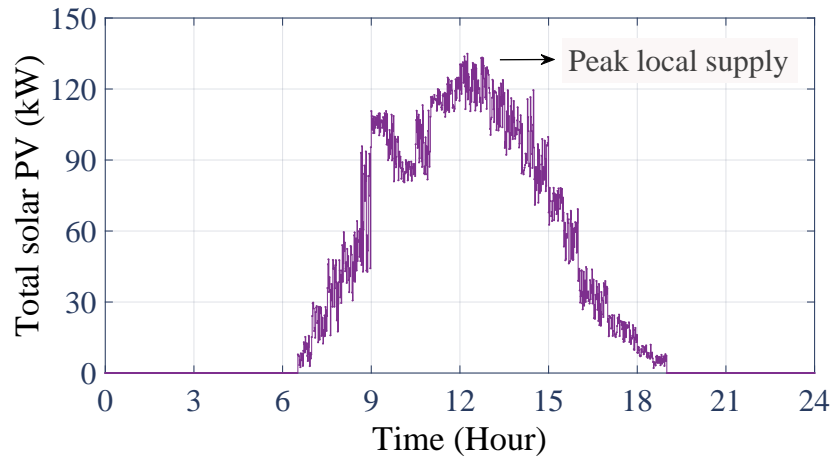


Fig. 3: This figure describes the single-line diagram of a 415V unbalanced LV network in Australia.



(a) Total demand.



(b) Total local solar PV supply.

Fig. 4: This figure displays the total demand and local solar PV supply in the network for a typical sunny day.

### A. Electricity Cost Reduction

This sub-section explains the effect of proposed trading mechanism on each nW P2P prosumer's electricity cost for a typical day. The nW prosumers are ordered in the sequence they are located in the physical network as illustrated in the first two columns of Table IV. After executing of each successful cooperative nW trading, every prosumer is awarded with its benefit using Shapley value and Nucleolus. Fig. 5 captures the benefit of each prosumer in Australian cents according to Shapley value and Nucleolus (calculated through MatTuGames [45]) at a given trading interval, in which 22 kW power is traded in total between 18 prosumers via P2P coalition. In this case, Shapley value has been calculated within 317.7 ms, whereas it has taken 1064.8 ms to calculate the Nucleolus. That means, around 3.3 times more computational time has been required to calculate Nucleolus compared to the Shapley Value.

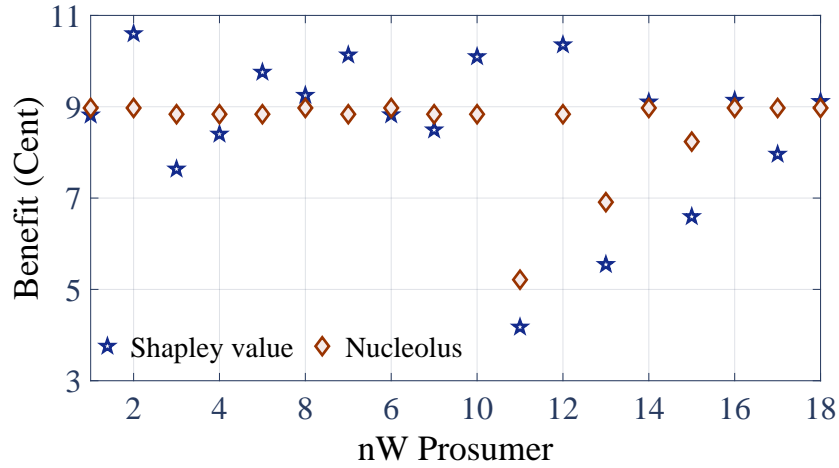


Fig. 5: This figure captures the benefit of each participating nW prosumer based on Shapley value and Nucleolus at a given trading interval.

The overall energy cost analysis of all nW prosumers over the course of 24 hours is demonstrated in Table IV. Here, Case I and Case II represent the demand response strategy and the proposed nW P2P trading framework respectively. Table IV suggests that the percentage electricity expense minimisation to each nW P2P prosumer can fluctuate between nearly 9.4% and 23.4%. In particular, Prosumers 1, 7, 9, 14 and 17 are billed \$5.1057, \$5.7134, \$4.8858, \$7.9554 and \$7.6211 respectively for a given day in Case I. Strikingly, these figures decline to \$4.0591, \$4.6467, \$3.8601, \$6.8432 and \$6.5702 respectively when these prosumers decide to join in the proposed nW P2P trading (Case II). Consequently, Prosumers 1, 7, 9, 14 and 17 can save approximately \$1.04, \$1.07, \$1.03, \$1.11 and \$1.05 or can get percentage savings of 20.49%, 18.67%, 20.99%, 13.98% and 13.79% respectively. All other prosumers also decrease their electricity bill quantities in line with their engagement in the nW P2P coalition.

### B. Physical Deployment Impacts

The repercussion of modifications in the power demand of the involving nW prosumers on the actual network, illustrated in Fig. 3, is investigated in this sub-section. The physical impact of the proposed CCG model is discovered in two steps:

- Step 1:** Perform a power flow study, where nW P2P traded quantities are assumed to be zero, which is called Case I.
- Step 2:** Repeat the power flow study with the solution of the proposed CCG framework, which is termed as Case II.

TABLE IV: Electricity cost analysis of nW P2P prosumers for a typical sunny day.

nW Prosumer	Physical location	Cost in Case I (AUD)	Cost in Case II (AUD)	Cost reduction (AUD)	% Cost reduction
Prosumer 1	Node 5a	5.1057	4.0591	1.0466	20.4977%
Prosumer 2	Node 5b	6.4257	5.1905	1.2352	19.2225%
Prosumer 3	Node 5c	9.5792	8.4653	1.1139	11.6283%
Prosumer 4	Node 6a	8.2771	7.2528	1.0243	12.3752%
Prosumer 5	Node 6b	8.1293	6.9557	1.1736	14.4371%
Prosumer 6	Node 6c	8.2322	7.0883	1.1439	13.8958%
Prosumer 7	Node 7a	5.7134	4.6467	1.0667	18.6700%
Prosumer 8	Node 7b	5.6558	4.5561	1.0997	19.4433%
Prosumer 9	Node 7c	4.8858	3.8601	1.0257	20.9935%
Prosumer 10	Node 8a	4.8396	3.7059	1.1336	23.4242%
Prosumer 11	Node 8b	9.8757	8.8556	1.0201	10.3292%
Prosumer 12	Node 8c	11.424	10.349	1.0745	09.4058%
Prosumer 13	Node 9a	7.1918	6.1062	1.0856	15.0948%
Prosumer 14	Node 9b	7.9554	6.8432	1.1122	13.9799%
Prosumer 15	Node 9c	8.6541	7.6298	1.0243	11.8360%
Prosumer 16	Node 10a	9.6350	8.5636	1.0714	11.1197%
Prosumer 17	Node 10b	7.6211	6.5702	1.0509	13.7897%
Prosumer 18	Node 10c	8.9033	7.8770	1.0263	11.5271%

Please note that same solar PV, load and battery profiles as well as network topology are considered to execute power flow on OpenDSS-interfaced MATLAB [46] platform for both Case I and Case II. Thus, a comparison between the power flow results can figure out the technical feasibility of the proposed nW P2P trading mechanism.

1) *Power Losses Assessment:* This part discusses how nW P2P trading can alter the power losses in the network. Table V describes the hourly power losses created in the network due to the proposed nW P2P trading (Case II) in comparison with the Case I, where there exists no nW trading between the prosumers. For instance, 7.0343 kW power loss is caused in Case II at 8 pm, which is 1.2668 kW fewer than Case I. This is because buyers situated close to the distribution sub-station request sellers to decrease 14 kW of demand in total. As such, less amount of supplied power travels through the network branches to reach the far-off nodes, resulting in reduced power loss. Following the same principle, On the other hand, the designed trading mechanism enhances 1.0247 kW power loss in the network at 8 am as distant prosumers act as nW buyers during this time slot. In fact, there is no power loss difference between Case I and Case II if no nW P2P transaction is performed, e.g., at 1 am. Importantly, the designed nW P2P trading does not change the overall power loss substantially. In particular, around 0.69 kW daily power loss is varied in total, which is only 0.9% and ¢35.97 in financial value.

However, the power loss can differ marginally on day-to-day basis in accordance with the physical location of the nW traders. If significant variation is found at the transmission/micrgrid level, the network constraints should be considered in the nW P2P model to minimise the network losses similar to [47].

2) *Voltage Profiles' Assessment:* The effect of the proposed nW P2P trading on the network voltage is discovered in this part. The upper and lower voltage limits of the test network, shown in Fig. 3, are set to 1.05 pu and 0.9 pu respectively [48]. Fig. 6 exhibits three-phase voltages at a comparatively high nW P2P trading period, in which 25 kW power is reduced in total by the sellers. Although the voltage profiles of Phase a and Phase c mostly remain unvaried, some node voltages of Phase b are improved slightly compared to Case I due to the fact of considerable demand reduction in those nodes.

TABLE V: Power losses assessment in the network.

Hour	Case I (kW)	Case II (kW)	Variation (kW)
1 am	0.8151	0.8151	0
2 am	0.4662	0.4662	0
3 am	0.729	0.729	0
4 am	0.4603	0.4603	0
5 am	1.3353	1.3353	0
6 am	2.3546	2.4443	+0.0897
7 am	4.4647	4.3207	-0.1440
8 am	4.1175	5.1422	+1.0247
9 am	1.9639	2.0489	+0.0085
10 am	0.8681	0.8681	0
11 am	0.7572	0.7572	0
12 pm	1.0981	1.0981	0
1 pm	1.0598	1.0598	0
2 pm	0.7177	0.7177	0
3 pm	1.2630	1.3792	+0.1167
4 pm	1.2478	1.2009	-0.0469
5 pm	6.8487	6.7934	-0.0553
6 pm	8.9034	9.3560	+0.4526
7 pm	12.1834	10.7857	-1.3977
8 pm	8.3011	7.0343	-1.2668
9 pm	8.8768	9.9094	+0.2172
10 pm	4.1907	4.2985	+0.1078
11 pm	1.5362	1.5143	-0.0119
12 am	1.2401	1.3837	+0.1436
24 hours	75.7887	75.1029	-0.6858

The consequence of low nW P2P trading, i.e., total 5 kW power is reduced at the sellers' nodes, on the three-phase voltages is depicted in Fig. 7. In this case, minimal fluctuation in voltage profiles is found at all three phases. Hence, the designed nW P2P trading framework does not impact the network voltages unfavourably.

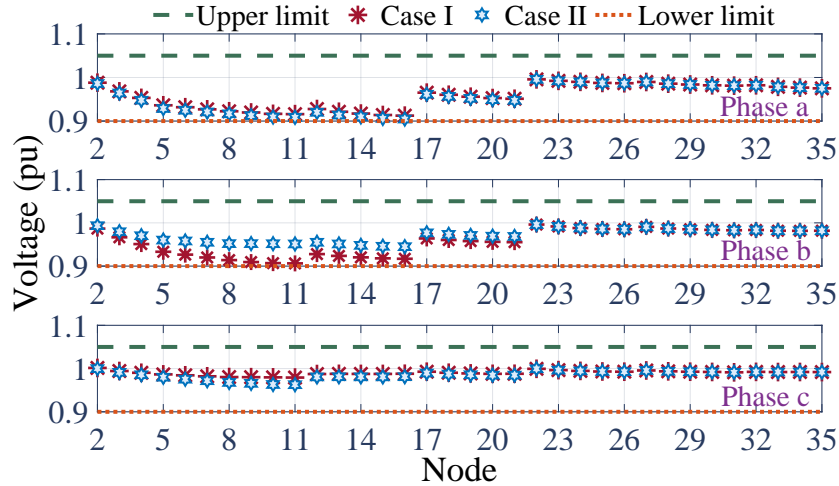


Fig. 6: This figure exhibits the voltage profiles at a comparatively high nW P2P trading period.

3) *Comparison with kW P2P Trading:* The physical performance of the proposed nW P2P trading is compared with the kW P2P trading [36] in this sub-section with the intention of analysing the influence on the node voltages. Assume a buyer (located at Phase c of node 27) requires 5 kW power and strikes a trading deal with a selling prosumer connected at node 10

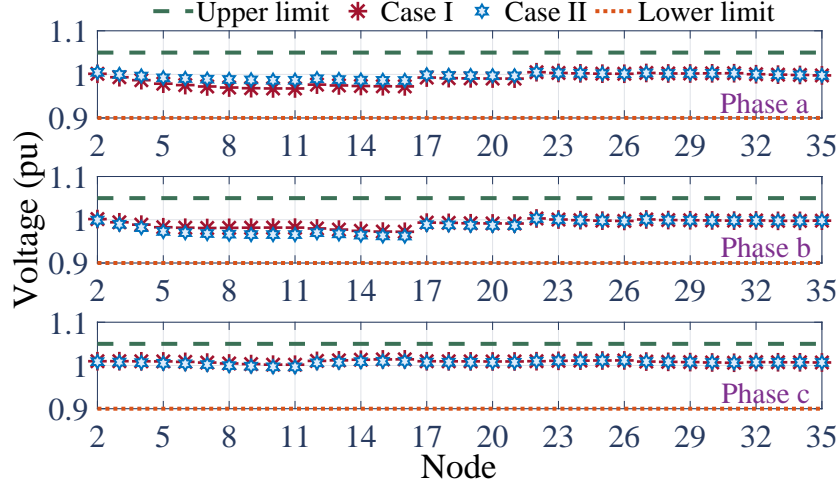


Fig. 7: This figure depicts the voltage profiles at a low nW P2P trading period.

of the same phase at a given time slot  $t$ . In kW P2P trading scenario, the seller at node 10c injects its 5 kW power surplus into the network, where its power configuration are:  $P_{10c,t}^b = 1$  kW,  $P_{10c,t}^f = 2$  kW,  $P_{10c,t}^{pv} = 5$  kW, and  $P_{10c,t}^{batt} = -3$  kW.

To carry out nW P2P trading, in contrast, the seller at node 10c reduces its 5 kW demand. In this scenario, the power configuration of the seller are:  $P_{10c,t}^b = 1$  kW,  $P_{10c,t}^f = 2$  kW,  $P_{10c,t}^{pv} = 0$  kW, and  $P_{10c,t}^{batt} = 3$  kW. Please note that the power demand and local supply of all other nodes along with the network topology are considered identical for both types of P2P trading scenarios.

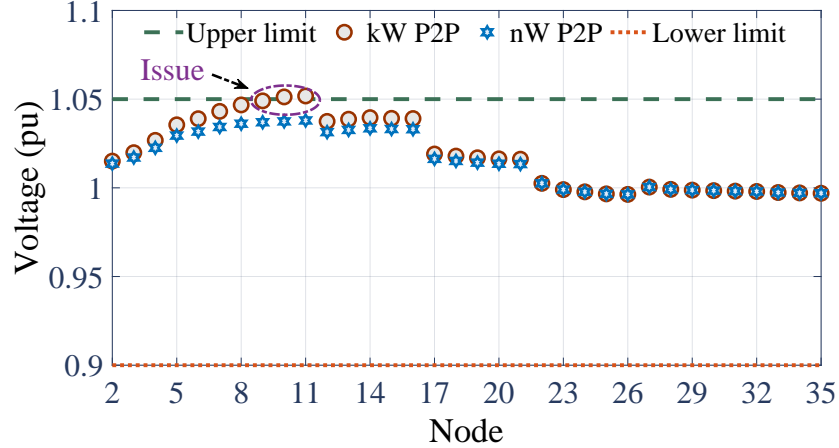


Fig. 8: This figure illustrates the voltage profiles of Phase c during kW and nW P2P trading.

Fig. 8 illustrates the node voltages of Phase c during kW and nW P2P tradings. As is seen that voltage rise issue is caused by the kW P2P trading at nodes 9, 10 and 11 because of unregulated reverse power flow in the network. A regulated kW P2P trading mechanism can be formulated to eradicate the over-voltage problem. As opposed to kW P2P trading, no high voltage complexity is noticed in case of nW P2P trading as there is no local export at the contracted seller's node. Thus, the nW P2P trading is safe for the considered LV network.

Based on the simulation results, it is stated that nW P2P trading do not violate network constraints like kW P2P trading. As such, network protection schemes have not been implemented in this paper to modify nW P2P traded power.

The proposed trading model is built in OpenDSS-interfaced MATLAB platform on a personal computer with a processor of 3.6 GHz Intel (R) Core (TM) i7–7700 and a memory of 16 GB. Fig. 9 indicates that the number of iterations and computational time required to converge the designed nW P2P framework rely on the number of participating prosumers. For instance, 3, 9 and 18 prosumers' participation at each nW P2P trading instant need 1, 3 and 5 iterations, which take approximately 0.89 s, 2.68 s and 5.36 s to converge. In total, the whole day simulation (summation of all trading slots) of the developed nW P2P trading model takes around 2.51 minutes to provide the results.

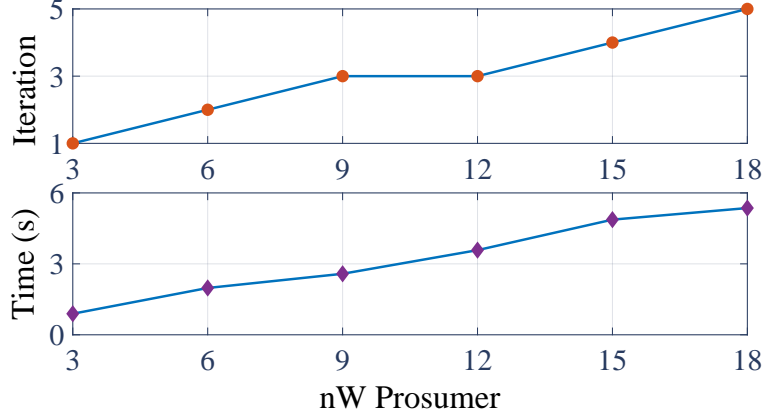


Fig. 9: This figure describes the iterations and computational time required to converge the proposed nW P2P model.

## V. CONCLUSION

This paper emphasises on developing a new nW P2P trading model to cut down prosumers' energy expenses without jeopardising the physical constraints of the distribution network. To do so, a coalition game-theoretic framework has been proposed, whereby all the interested prosumers have executed nW P2P trading collaboratively. The relevant properties of the nW P2P coalition have been validated to articulate that it is beneficial, stable and user-centric for the participating prosumers. Moreover, the total benefit of the proposed coalition has been allocated fairly between nW prosumers. Finally, simulation results have been presented to demonstrate the applicability of the designed nW P2P mechanism in real distribution networks. It has been observed that the cooperative framework can permit each prosumer to reduce its daily electricity cost by around \$1 through proposed nW trading. Certainly, this can motivate them to engage in the new nW P2P business model. In addition, the impact of the developed model on the physical network in terms of power losses and voltage profiles has been found to be insignificant. As such, no technical limit violations have been noticed in the network. Therefore, the proposed nW P2P trading mechanism is suitable for practical deployment without including power flow constraints as direct constraint in the algorithm.

Future research can be carried out to investigate how the large-sized prosumers' participation in nW P2P trading impacts the network losses at the transmission/micrgrid level. Besides, nW P2P price function can be determined through optimisation to minimise the overall costs further for the whole coalition. Lastly, the roles and benefits of various stakeholders can be integrated in the nW P2P trading framework to demonstrate its suitability in the real energy market.

## APPENDIX I (COALITION PRELIMINARIES)

Let  $\mathcal{L} \in \mathbf{2}^{\mathcal{X}}, \forall \mathcal{L} \subseteq \mathcal{X}$  be any subset of the grand coalition  $\mathcal{X}$ , where  $\mathbf{2}^{\mathcal{X}}$  implies the set of all possible coalitions. The size of the grand coalition  $\mathcal{X}$  and operational times' set  $\mathcal{T}$  are denoted by  $X = |\mathcal{X}|$  and  $T = |\mathcal{T}|$  respectively. A matrix  $\mathbf{A} \in \mathbb{R}^{X \times T}$  is defined as:

$$\mathbf{A} \in \mathbb{R}^{X \times T} := [\mathbf{a}_1, \mathbf{a}_2, \dots, \mathbf{a}_X] \quad (\text{I. 1})$$

where  $\mathbf{a}_x \in \mathbb{R}^T, \forall x \in \{1, 2, \dots, X\}$ , indicates a column vector.

For any coalition  $\mathcal{L}_d$  and scalar constant  $q_k \geq 0, \forall k \in \mathbf{2}^X$ , where the set  $\mathbf{2}^X := \{1, 2, \dots, 2^X\}$ , the coalition scaling is expressed as [37]:

$$\mathbf{A}(q_k \mathcal{L}_d) = [q_k \mathbf{a}_1 1_1(\mathcal{L}_d), q_k \mathbf{a}_2 1_2(\mathcal{L}_d), \dots, q_k \mathbf{a}_X 1_X(\mathcal{L}_d)] = q_k [\mathbf{a}_1 1_1(\mathcal{L}_d), \mathbf{a}_2 1_2(\mathcal{L}_d), \dots, \mathbf{a}_X 1_X(\mathcal{L}_d)] = q_k \mathbf{A}(\mathcal{L}_d) \quad (\text{I. 2})$$

where  $1_x(\mathcal{L}_d)$  symbolises the  $x^{\text{th}}$  element of vector  $\mathbf{1}(\mathcal{L}) \in \mathbb{R}^X$  defined in (I. 3).

$$1_x(\mathcal{L}_d) = \begin{cases} 1, & \text{if } x \in \mathcal{L}_d \\ 0, & \text{otherwise} \end{cases} \quad (\text{I. 3})$$

The coalition summation is computed as:

$$\begin{aligned} \mathbf{A}(\sum_{k \in \mathbf{2}^X} q_k \mathcal{L}_d) &= \left[ \sum_{k \in \mathbf{2}^X} q_k \mathbf{a}_1 1_1(\mathcal{L}_d), \sum_{k \in \mathbf{2}^X} q_k \mathbf{a}_2 1_2(\mathcal{L}_d), \dots, \sum_{k \in \mathbf{2}^X} q_k \mathbf{a}_X 1_X(\mathcal{L}_d) \right] \\ &= \sum_{k \in \mathbf{2}^X} q_k [\mathbf{a}_1 1_1(\mathcal{L}_d), \mathbf{a}_2 1_2(\mathcal{L}_d), \dots, \mathbf{a}_X 1_X(\mathcal{L}_d)] = \sum_{k \in \mathbf{2}^X} q_k \mathbf{A}(\mathcal{L}_d) \end{aligned} \quad (\text{I. 4})$$

Assume two disjoint coalitions  $\mathcal{L}_d \in \mathbf{2}^X$  and  $\mathcal{L}_z \in \mathbf{2}^X$  and scalars  $q_k = q_z = 1$  such that:

$$1_x(\mathcal{L}_d) + 1_x(\mathcal{L}_z) = 1_x(\mathcal{L}_d \cup \mathcal{L}_z), \quad \forall x \in \mathcal{X} \quad (\text{I. 5a})$$

$$\begin{aligned} \mathbf{A}(\mathcal{L}_d + \mathcal{L}_z) &= \mathbf{A}(\mathcal{L}_d) + \mathbf{A}(\mathcal{L}_z) = [\mathbf{a}_1 (1_1(\mathcal{L}_d) + 1_1(\mathcal{L}_z)), \mathbf{a}_2 (1_2(\mathcal{L}_d) + 1_2(\mathcal{L}_z)), \dots, \mathbf{a}_X (1_X(\mathcal{L}_d) + 1_X(\mathcal{L}_z))] \\ &= [\mathbf{a}_1 1_1(\mathcal{L}_d \cup \mathcal{L}_z), \mathbf{a}_2 1_2(\mathcal{L}_d \cup \mathcal{L}_z), \dots, \mathbf{a}_X 1_X(\mathcal{L}_d \cup \mathcal{L}_z)] = \mathbf{A}(\mathcal{L}_d \cup \mathcal{L}_z) \end{aligned} \quad (\text{I. 5b})$$

where  $\mathcal{L}_d \cap \mathcal{L}_z = \{\phi\}, \forall k, z \in \mathbf{2}^X$ .

## APPENDIX II (PROOF OF THEOREM 1)

*Proof.* For any scalar  $q \geq 0$ , the total electricity cost of coalition  $\mathcal{L}$  can be expressed as:

$$\begin{aligned} \Pi_{\mathcal{L}}(q \Gamma(\mathcal{L})) &= [(\lambda^m)^\top q (\mathbf{P}^s(\mathcal{L}) \mathbf{1} + \mathbf{P}^b(\mathcal{L}) \mathbf{1})] + [(\lambda^n)^\top q (\mathbf{P}^i(\mathcal{L}) \mathbf{1} - \mathbf{P}^r(\mathcal{L}) \mathbf{1})] \\ &= q [(\lambda^m)^\top (\mathbf{P}^s(\mathcal{L}) \mathbf{1} + \mathbf{P}^b(\mathcal{L}) \mathbf{1})] + q [(\lambda^n)^\top (\mathbf{P}^i(\mathcal{L}) \mathbf{1} - \mathbf{P}^r(\mathcal{L}) \mathbf{1})] \\ &= q ([(\lambda^m)^\top (\mathbf{P}^s(\mathcal{L}) \mathbf{1} + \mathbf{P}^b(\mathcal{L}) \mathbf{1})] + [(\lambda^n)^\top (\mathbf{P}^i(\mathcal{L}) \mathbf{1} - \mathbf{P}^r(\mathcal{L}) \mathbf{1})]) = q \Pi_{\mathcal{L}}(\Gamma(\mathcal{L})) \end{aligned} \quad (\text{II. 1})$$

The convex cost function of two disjoint coalitions  $\mathcal{L}_d \in \mathbf{2}^{\mathcal{X}}$  and  $\mathcal{L}_z \in \mathbf{2}^{\mathcal{X}}$  can be written as:

$$\begin{aligned} & \frac{\Pi_{\mathcal{L}_d}(\mathbf{\Gamma}(\mathcal{L}_d)) + \Pi_{\mathcal{L}_z}(\mathbf{\Gamma}(\mathcal{L}_z))}{2} = \\ & \frac{[(\boldsymbol{\lambda}^m)^\top ([\mathbf{P}^s(\mathcal{L}_d) \mathbf{1} + \mathbf{P}^s(\mathcal{L}_z) \mathbf{1}] + [\mathbf{P}^b(\mathcal{L}_d) \mathbf{1} + \mathbf{P}^b(\mathcal{L}_z) \mathbf{1}]) + [(\boldsymbol{\lambda}^n)^\top ([\mathbf{P}^i(\mathcal{L}_d) \mathbf{1} + \mathbf{P}^i(\mathcal{L}_z) \mathbf{1}] - [\mathbf{P}^r(\mathcal{L}_d) \mathbf{1} + \mathbf{P}^r(\mathcal{L}_z) \mathbf{1}])]}{2} = \\ & \frac{[(\boldsymbol{\lambda}^m)^\top ([\mathbf{P}^s(\mathcal{L}_d) \mathbf{1} + \mathbf{P}^s(\mathcal{L}_z) \mathbf{1}] + [\mathbf{P}^b(\mathcal{L}_d) \mathbf{1} + \mathbf{P}^b(\mathcal{L}_z) \mathbf{1}])]}{2} + \frac{[(\boldsymbol{\lambda}^n)^\top ([\mathbf{P}^i(\mathcal{L}_d) \mathbf{1} + \mathbf{P}^i(\mathcal{L}_z) \mathbf{1}] - [\mathbf{P}^r(\mathcal{L}_d) \mathbf{1} + \mathbf{P}^r(\mathcal{L}_z) \mathbf{1}])]}{2} \geq \quad (\text{II. 2}) \\ & \frac{[(\boldsymbol{\lambda}^m)^\top (\mathbf{P}^s(\mathcal{L}_d + \mathcal{L}_z) + \mathbf{P}^b(\mathcal{L}_d + \mathcal{L}_z))]}{2} + \frac{[(\boldsymbol{\lambda}^n)^\top (\mathbf{P}^i(\mathcal{L}_d + \mathcal{L}_z) - \mathbf{P}^r(\mathcal{L}_d + \mathcal{L}_z))]}{2} = \Pi_{\mathcal{L}_d + \mathcal{L}_z} \left( \frac{\mathbf{\Gamma}(\mathcal{L}_d + \mathcal{L}_z)}{2} \right) \end{aligned}$$

Now, the sum of optimum cost function of two disjoint coalitions  $\mathcal{L}_d$  and  $\mathcal{L}_z$  is:

$$\sigma(\mathcal{L}_d) + \sigma(\mathcal{L}_z) = \Pi_{\mathcal{L}_d}(\mathbf{\Gamma}(\tilde{\mathcal{L}}_d)) + \Pi_{\mathcal{L}_z}(\mathbf{\Gamma}(\tilde{\mathcal{L}}_z)) \geq 2 \left( \Pi_{\mathcal{L}_d + \mathcal{L}_z} \left( \frac{\mathbf{\Gamma}(\tilde{\mathcal{L}}_d + \tilde{\mathcal{L}}_z)}{2} \right) \right) = \Pi_{\mathcal{L}_d + \mathcal{L}_z}(\mathbf{\Gamma}(\tilde{\mathcal{L}}_d + \tilde{\mathcal{L}}_z)) \quad (\text{II. 3})$$

where  $\mathbf{\Gamma}(\tilde{\mathcal{L}})$  is considered as the optimal solution of (20) such that:

$$\sigma(\mathcal{L}) = \Pi_{\mathcal{L}}(\mathbf{\Gamma}(\tilde{\mathcal{L}})) \quad (\text{II. 4a})$$

$$\Pi_{\mathcal{L}}(\mathbf{\Gamma}(\tilde{\mathcal{L}})) \leq \Pi_{\mathcal{L}}(\mathbf{\Gamma}(\mathcal{L})), \quad \forall \mathbf{\Gamma}(\mathcal{L}) \in \mathcal{F}(\mathcal{L}) \quad (\text{II. 4b})$$

The indicator function and corresponding feasible set of coalition  $\mathcal{L}_d + \mathcal{L}_z$  are:

$f(\mathbf{\Gamma}(\mathcal{L}_d + \mathcal{L}_z), \overline{\mathbf{P}}^f(\mathcal{L}_d + \mathcal{L}_z), \overline{\mathbf{W}}(\mathcal{L}_d + \mathcal{L}_z), \overline{\rho}(\mathcal{L}_d + \mathcal{L}_z))$  and  $\mathcal{F}(\mathcal{L}_d + \mathcal{L}_z)$  respectively.

Given that  $f(\mathbf{\Gamma}(\tilde{\mathcal{L}}_d), \overline{\mathbf{P}}^f(\mathcal{L}_d), \overline{\mathbf{W}}(\mathcal{L}_d), \overline{\rho}(\mathcal{L}_d)) = 1$  and  $f(\mathbf{\Gamma}(\tilde{\mathcal{L}}_z), \overline{\mathbf{P}}^f(\mathcal{L}_z), \overline{\mathbf{W}}(\mathcal{L}_z), \overline{\rho}(\mathcal{L}_z)) = 1$ ,  $\mathbf{\Gamma}(\tilde{\mathcal{L}}_d + \tilde{\mathcal{L}}_z) \in \mathcal{F}(\mathcal{L}_d + \mathcal{L}_z)$ .

From (II. 4a) and (II. 4b),

$$\Pi_{\mathcal{L}_d + \mathcal{L}_z}(\mathbf{\Gamma}(\tilde{\mathcal{L}}_d + \tilde{\mathcal{L}}_z)) \geq \Pi_{\mathcal{L}_d + \mathcal{L}_z}(\mathbf{\Gamma}(\mathcal{L}_d + \mathcal{L}_z)) = \sigma(\mathcal{L}_d + \mathcal{L}_z) \quad (\text{II. 5})$$

By combining (II. 3) and (II. 5),

$$\sigma(\mathcal{L}_d) + \sigma(\mathcal{L}_z) \geq \sigma(\mathcal{L}_d + \mathcal{L}_z) \implies -\sigma(\mathcal{L}_d + \mathcal{L}_z) \geq -(\sigma(\mathcal{L}_d) + \sigma(\mathcal{L}_z)) \quad (\text{II. 6})$$

By adding  $\sum_{x \in \mathcal{L}_d} \sigma(\{x\}) + \sum_{x \in \mathcal{L}_z} \sigma(\{x\})$  in (II. 6) and using (19),

$$\begin{aligned} & \sum_{x \in \mathcal{L}_d} \sigma(\{x\}) + \sum_{x \in \mathcal{L}_z} \sigma(\{x\}) - \sigma(\mathcal{L}_d + \mathcal{L}_z) \geq \sum_{x \in \mathcal{L}_d} \sigma(\{x\}) + \sum_{x \in \mathcal{L}_z} \sigma(\{x\}) - (\sigma(\mathcal{L}_d) + \sigma(\mathcal{L}_z)) \\ \implies & \sum_{x \in (\mathcal{L}_d \cup \mathcal{L}_z)} \sigma(\{x\}) - \sigma(\mathcal{L}_d \cup \mathcal{L}_z) \geq \left( \sum_{x \in \mathcal{L}_d} \sigma(\{x\}) - \sigma(\mathcal{L}_d) \right) + \left( \sum_{x \in \mathcal{L}_z} \sigma(\{x\}) - \sigma(\mathcal{L}_z) \right) \quad (\text{II. 7}) \\ \implies & \nu(\mathcal{L}_d \cup \mathcal{L}_z) \geq \nu(\mathcal{L}_d) + \nu(\mathcal{L}_z) \end{aligned}$$

(II. 7) suggests that  $\nu$  reduces with increase of disjoint coalitions. Therefore, the value function of the proposed CCG is superadditive such that no nW prosumer can benefit better by deviating from the P2P coalition.  $\square$



## APPENDIX III (PROOF OF THEOREM 2)

*Proof.* If any scalar  $q = 0$ , (20) can be rewritten using (I. 2) as:

$$\sigma(q \mathcal{L}) = \sigma(0 \mathcal{L}) = \min_{\Gamma(\mathcal{L}) \in \mathcal{F}(\mathcal{L})} \Pi_{0 \mathcal{L}}(\Gamma(0 \mathcal{L})) = 0 = 0 \sigma(\mathcal{L}) = q \sigma(\mathcal{L}) \quad (\text{III. 1})$$

If  $q > 0$ , based on (20) and (II. 4a),

$$\sigma(q \mathcal{L}) = \Pi_{q \mathcal{L}}(\Gamma(q \tilde{\mathcal{L}})) \quad (\text{III. 2a})$$

$$f(\Gamma(q \tilde{\mathcal{L}}), \overline{\mathbf{P}^f}(q \mathcal{L}), \overline{\mathbf{W}}(q \mathcal{L}), \overline{\rho}(q \mathcal{L})) = 1 \quad (\text{III. 2b})$$

Since the constraints defined in (18a)-(18d) are linear, whenever  $f(\Gamma(\tilde{\mathcal{L}}), \overline{\mathbf{P}^f}(\mathcal{L}), \overline{\mathbf{W}}(\mathcal{L}), \overline{\rho}(\mathcal{L})) = 1$ ,  $f(\Gamma(\frac{1}{q} \tilde{\mathcal{L}}), \overline{\mathbf{P}^f}(\frac{1}{q} \mathcal{L}), \overline{\mathbf{W}}(\frac{1}{q} \mathcal{L}), \overline{\rho}(\frac{1}{q} \mathcal{L})) = 1$ . Thus,  $\frac{1}{q} \Gamma(q \tilde{\mathcal{L}})$  belongs to  $\mathcal{F}(\mathcal{L})$ .

Applying (II. 1) in (II. 4a) and (II. 4b),

$$\sigma(\mathcal{L}) = \Pi_{\mathcal{L}}(\Gamma(\tilde{\mathcal{L}})) \leq \Pi_{\mathcal{L}}\left(\frac{1}{q} \Gamma(q \tilde{\mathcal{L}})\right) = \frac{1}{q} \Pi_{\mathcal{L}}(\Gamma(q \tilde{\mathcal{L}})) = \frac{1}{q} \sigma(q \mathcal{L}) \quad (\text{III. 3})$$

Hence,  $\sigma(q \mathcal{L}) \geq q \sigma(\mathcal{L}), \forall q > 0$ .

For scalar  $\frac{1}{q} > 0$ ,

$$\sigma(\mathcal{L}) = \sigma\left(\frac{1}{q} (q \mathcal{L})\right) \geq \frac{1}{q} \sigma(q \mathcal{L}) \quad (\text{III. 4})$$

Now,

$$\sigma(q \mathcal{L}) \geq q \sigma(\mathcal{L}) \geq q \frac{1}{q} \sigma(q \mathcal{L}) = \sigma(q \mathcal{L}) \quad (\text{III. 5})$$

.

The grand coalition value equals to:

$$\nu(\mathcal{X}) = \sum_{x \in \mathcal{X}} \sigma(\{x\}) - \sigma(\mathcal{X}) \quad (\text{III. 6})$$

For any balanced collection of weights  $\gamma(\mathcal{L})$ ,

$$\begin{aligned} \sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) \nu(\mathcal{L}) &= \sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) \left( \sum_{x \in \mathcal{L}} \sigma(\{x\}) - \sigma(\mathcal{L}) \right) = \sum_{x \in \mathcal{L}} \sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) \sigma(\{x\}) - \sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) \sigma(\mathcal{L}) \\ &= \sum_{x \in \mathcal{X}} \sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) 1_x(\mathcal{L}) \sigma(\{x\}) - \sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) \sigma(\mathcal{L}) = \sum_{x \in \mathcal{X}} \sigma(\{x\}) - \sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) \sigma(\mathcal{L}) \end{aligned} \quad (\text{III. 7})$$

where  $\sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) 1_x(\mathcal{L}) = 1$ .

Combining (III. 6) and (III. 7), the condition of the proposed CCG to be balanced is:

$$\sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) \sigma(\mathcal{L}) \geq \sigma(\mathcal{X}) \quad (\text{III. 8})$$

Considering the non-negativity of  $\gamma(\mathcal{L}) \in [0, 1]$  and utilising (III. 5) and (20):

$$\begin{aligned} \sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) \sigma(\mathcal{L}) &= \sum_{\mathcal{L} \in 2^{\mathcal{X}}} \sigma(\gamma(\mathcal{L}) \mathcal{L}) \geq \sigma \left( \sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) \mathcal{L} \right) \\ &= \min_{\mathbf{r}(\sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) \mathcal{L}) \in \mathcal{F}(\sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) \mathcal{L})} \left[ \Pi_{\sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) \mathcal{L}} \left( \Gamma \left( \sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) \mathcal{L} \right) \right) \right] \end{aligned} \quad (\text{III. 9})$$

$\sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) \mathcal{L}$  can be expressed as:

$$\begin{aligned} \sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) \mathcal{L} &= \sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) \bigcup_{x \in \mathcal{L}} \{x\} = \sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) \sum_{x \in \mathcal{L}} \{x\} = \sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) \sum_{x \in \mathcal{X}} 1_x(\mathcal{L}) \{x\} \\ &= \sum_{x \in \mathcal{X}} \sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) 1_x(\mathcal{L}) \{x\} = \sum_{x \in \mathcal{X}} \{x\} = \bigcup_{x \in \mathcal{X}} \{x\} = \mathcal{X} \end{aligned} \quad (\text{III. 10})$$

Now, (III. 9) can be rewritten as:

$$\sum_{\mathcal{L} \in 2^{\mathcal{X}}} \gamma(\mathcal{L}) \sigma(\mathcal{L}) \geq \min_{\mathbf{r}(\mathcal{X}) \in \mathcal{F}(\mathcal{X})} \Pi_{\mathcal{X}}(\Gamma(\mathcal{X})) = \sigma(\mathcal{X}) \quad (\text{III. 11})$$

Thus, the condition of (III. 8) is satisfied. Therefore, the proposed CCG is balanced, resulting in stable nW prosumers' coalition.

□

## REFERENCES

- [1] A. B. Lovins, "Saving gigabucks with negawatts," *Public Utilities Fortnightly*, vol. 115, no. 6, pp. 19–26, 1985.
- [2] W. Tushar, T. K. Saha, C. Yuen, D. Smith, P. Ashworth, H. V. Poor, and S. Basnet, "Challenges and prospects for negawatt trading in light of recent technological developments," *Nature Energy*, pp. 1–8, Aug. 2020.
- [3] A. B. Lovins, "The negawatt revolution," *Across the Board*, vol. 27, no. 9, pp. 18–23, Sep. 1990.
- [4] Y. Okawa and T. Namerikawa, "Distributed power supply-demand management based on negawatt trading with energy storage system," in *Proc. of the European Control Conference, Aalborg, Denmark*, pp. 1812–1817, Jun./Jul. 2016.
- [5] Z. Jing, M. Pipattanasomporn, and S. Rahman, "Blockchain-based negawatt trading platform: Conceptual architecture and case studies," in *IEEE PES GTD Grand International Conference and Exposition Asia, Bangkok, Thailand*, pp. 68–73, May 2019.
- [6] "What is the price of a negawatt?," <https://www.e-education.psu.edu/ebf483/node/716>.
- [7] S. Tomic, "Economic effects of trading watts and negawatts by agile customers in hierarchic energy markets," in *Proc. of the International Conference on the European Energy Market, Florence, Italy*, pp. 1–6, May 2012.
- [8] A. Algarni and T. Namerikawa, "Integrating demand response aggregators with negawatt trading mechanisms in electricity markets, wichita, usa," in *Proc. of the North American Power Symposium*, pp. 1–5, Oct. 2019.
- [9] A. Safari, M. Tahmasebi, and J. Pasupuleti, "Smart buildings aggregator bidding strategy as a negawatt demand response resources in the spinning reserve electricity market," in *Proc. of the IEEE PES Innovative Smart Grid Technologies Europe, Bucharest, Romania*, pp. 1–4, Sep.-Oct. 2019.
- [10] Y. Okawa and T. Namerikawa, "Distributed optimal power management via negawatt trading in real-time electricity market," *IEEE Transactions on Smart Grid*, vol. 8, no. 6, pp. 3009–3019, Nov. 2017.
- [11] K. Honda, K. Kusakiyo, S. Matsuzawa, M. Kosakada, and Y. Miyazaki, "Experiences of demand response in Yokohama demonstration project," *CIRED-Open Access Proceedings Journal*, pp. 1759–1762, Jun. 2017.
- [12] "Demand Response Trial," <https://arena.gov.au/news/aemo-arena-demand-response/>.
- [13] "Half of users abandon smart meter trial," *itnews*, Jan. 2014.
- [14] "Queensland solar bonus scheme policy guide," Oct. 2018.

- [15] D. Syptayev, H. K. Nunna, and A. Shintemirov, "A novel peer-to-peer negawatt trading transactive energy system for prosumers," in *Proc. of the International Conference on Compatibility, Power Electronics and Power Engineering, Setubal, Portugal*, pp. 181–186, Jul. 2020.
- [16] E. Mengelkamp, J. Gärtner, K. Rock, S. Kessler, L. Orsini, and C. Weinhardt, "Designing microgrid energy markets: A case study: The Brooklyn microgrid," *Applied Energy*, vol. 210, pp. 870–880, Feb. 2018.
- [17] M. I. Azim, W. Tushar, and T. K. Saha, "Coalition graph game-based P2P energy trading with local voltage management," *IEEE Transactions on Smart Grid (Early Access)*, doi:10.1109/TSG.2021.3070160, pp. 1–14, Mar. 2021.
- [18] Y. Jiang, K. Zhou, X. Lu, and S. Yang, "Electricity trading pricing among prosumers with game theory-based model in energy blockchain environment," *Applied Energy*, vol. 271, p. 115239, Aug. 2020.
- [19] M. I. Azim, S. A. Pourmousavi, W. Tushar, and T. K. Saha, "Feasibility study of financial P2P energy trading in a grid-tied power network," in *Proc. IEEE Power & Energy Society General Meeting, Atlanta, USA*, pp. 1–5, Aug. 2019.
- [20] M. I. Azim, W. Tushar, and T. K. Saha, "Investigating the impact of P2P trading on power losses in grid-connected networks with prosumers," *Applied Energy*, vol. 263, p. 114687, Apr. 2020.
- [21] W. Tushar, T. K. Saha, C. Yuen, D. Smith, and H. V. Poor, "Peer-to-peer trading in electricity networks: An overview," *IEEE Transactions on Smart Grid*, vol. 11, no. 4, pp. 3185–3200, Jul. 2020.
- [22] J. Guerrero, A. C. Chapman, and G. Verbič, "Decentralized P2P energy trading under network constraints in a low-voltage network," *IEEE Transactions on Smart Grid*, vol. 10, no. 5, pp. 5163–5173, Sep. 2019.
- [23] H. Almasalma, S. Claeys, and G. Deconinck, "Peer-to-peer-based integrated grid voltage support function for smart photovoltaic inverters," *Applied Energy*, vol. 239, pp. 1037–1048, Apr. 2019.
- [24] M. I. Azim, K. U. Z. Mollah, and H. R. Pota, "Design of a dynamic phasors-based droop controller for PV-based islanded microgrids," *International Transactions on Electrical Energy Systems*, vol. 28, no. 7, pp. 1–16, Jul. 2018.
- [25] M. I. Azim, W. Tushar, and T. K. Saha, "Regulated P2P energy trading: A typical Australian distribution network case study," in *Proc. IEEE Power & Energy Society General Meeting, Montreal, Canada*, pp. 1–5, Aug. 2020.
- [26] "Energy efficiency guide." [https://www.dnrme.qld.gov.au/\\_\\_data/assets/pdf\\_file/0009/1277181/energy-efficiency.pdf](https://www.dnrme.qld.gov.au/__data/assets/pdf_file/0009/1277181/energy-efficiency.pdf).
- [27] C. Long, J. Wu, Y. Zhou, and N. Jenkins, "Peer-to-peer energy sharing through a two-stage aggregated battery control in a community microgrid," *Applied energy*, vol. 226, pp. 261–276, Sep. 2018.
- [28] "Integrated system plan." <https://aemo.com.au/-/media/files/major-publications/isp/2020/final-2020-integrated-system-plan.pdf?la=en&hash=6BCC72F9535B8E5715216F8ECDB4451C>, Jul. 2020.
- [29] B. Hanumantha Rao, S. L. Arun, and M. P. Selvan, "An electric power trading framework for smart residential community in smart cities," *IET Smart Cities*, vol. 1, no. 2, pp. 40–51, Nov. 2019.
- [30] C. Zhang, J. Wu, Y. Zhou, M. Cheng, and C. Long, "Peer-to-peer energy trading in a microgrid," *Applied Energy*, vol. 220, pp. 1–12, Jun. 2018.
- [31] Y. Parag and B. K. Sovacool, "Electricity market design for the prosumer era," *Nature energy*, vol. 1, no. 4, p. 16032, Mar. 2016.
- [32] "Queensland electricity tariffs." <https://www.canstarblue.com.au/electricity/understanding-queensland-electricity-tariffs/>.
- [33] M. Farivar and S. H. Low, "Branch flow model: Relaxations and convexification—Part I," *IEEE Transactions on Power Systems*, vol. 28, no. 3, pp. 2554–2564, Aug. 2013.
- [34] R. D. Zimmerman, C. E. Murillo-Sánchez, R. J. Thomas, *et al.*, "Matpower: Steady-state operations, planning, and analysis tools for power systems research and education," *IEEE Transactions on Power Systems*, vol. 26, no. 1, pp. 12–19, Feb. 2011.
- [35] W. Saad, Z. Han, M. Debbah, A. Hjørungnes, and T. Basar, "Coalitional game theory for communication networks," *IEEE Signal Processing Magazine*, vol. 26, no. 5, pp. 77–97, Sep. 2009.
- [36] W. Tushar, T. K. Saha, C. Yuen, P. Liddell, R. Bean, and H. V. Poor, "Peer-to-peer energy trading with sustainable user participation: A game theoretic approach," *IEEE Access*, vol. 6, pp. 62932–62943, Oct. 2018.
- [37] J. Li, Y. Ye, D. Papadaskalopoulos, and G. Strbac, "Computationally efficient pricing and benefit distribution mechanisms for incentivizing stable peer-to-peer energy trading," *IEEE Internet of Things Journal*, vol. 8, no. 2, pp. 734–749, Jan. 2021.
- [38] W. Amin, Q. Huang, M. Afzal, A. A. Khan, K. Umer, and S. A. Ahmed, "A converging non-cooperative & cooperative game theory approach for stabilizing peer-to-peer electricity trading," *Electric Power Systems Research*, vol. 183, p. 106278, Jun. 2020.
- [39] M. Shipworth, "Motivating home energy action," *Australian Greenhouse Office*, Apr. 2000.
- [40] D. H. Hockenbury and S. E. Hockenbury, *Discovering psychology*. 2010.

- [41] L. Wang, R. Yan, and T. K. Saha, "Voltage regulation challenges with unbalanced PV integration in low voltage distribution systems and the corresponding solution," *Applied Energy*, vol. 256, p. 113927, Dec. 2019.
- [42] "Solar system size." <https://solarcalculator.com.au/solar-system-size/>.
- [43] "Solar battery storage." <https://solarcalculator.com.au/battery-storage/>.
- [44] W. Tushar, T. K. Saha, C. Yuen, M. I. Azim, T. Morstyn, H. V. Poor, D. Niyato, and R. Bean, "A coalition formation game framework for peer-to-peer energy trading," *Applied Energy*, vol. 261, p. 114436, Mar. 2020.
- [45] "MatTuGames: A Matlab Toolbox for Cooperative Game Theory." <https://au.mathworks.com/matlabcentral/fileexchange/74092-mattugames>.
- [46] "Simulation Tool: OpenDSS." <https://smartgrid.epri.com/SimulationTool.aspx>.
- [47] M. Hupez, J.-F. Toubreau, Z. De Grève, and F. Vallée, "A new cooperative framework for a fair and cost-optimal allocation of resources within a low voltage electricity community," *IEEE Transactions on Smart Grid*, vol. 12, no. 3, pp. 2201 – 2211, May 2021.
- [48] "Voltage limits regulation for Queensland." <https://www.parliament.qld.gov.au/Documents/TableOffice/TabledPapers/2018/5618T56.pdf>.