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A novel dynamic pricing model for a microgrid of prosumers with photovoltaic systems

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ABSTRACT

Due to the growing demand for electricity and the increasing number of consumers who can produce energy (prosumers) using photovoltaic systems today, energy generated by prosumers can be utilized in the microgrid instead of selling it to the main utility grid. Pricing is one of the most important mechanisms for motivating prosumers to interact with each other in the microgrid. Many works have proposed different pricing models that mostly focus on optimizing prosumers' behavior and energy usage costs. However, most of the proposed models require constant involvement of the end-user to adjust energy consumption profiles, which is not always possible in a real-world scenario. In this paper, a novel pricing model is presented with the aim of maximizing the utilization of energy generated in the microgrid and reducing the import of energy from the utility grid, whereas ensuring more beneficial prices for energy within the microgrid compared with the utility grid. Mathematical models based on the supply and demand ratio and prosumers' absolute deviation from the predicted energy usage profiles are developed to determine the internal equilibrium price and the amount of energy each prosumer can buy and sell by interacting with the microgrid. To cover the energy transfer losses in the microgrid, a dynamic loss allocation mechanism is proposed. The proposed pricing model is validated using real energy usage profiles from 100 prosumers. The results show that the total energy usage cost can be decreased, whereas the amount of unused energy that is shared outside the microgrid is minimized.

1. Introduction

Due to the increasing number of end-users, as well as the growing number of appliances used, the demand for electricity is constantly growing. The global demand for electricity is predicted to rise to 40,000 TWh by 2040 [1], which leads to an increase in energy generation on the utility side, where fossil fuels are the main sources of electricity production. For example, 68% of electricity was generated using coal-fired energy generation in Q1 2020 in China, whereas only 28% using Renewable Energy Sources (RES). The same situation is observed in India, where 77.5% of electricity was produced using coal in Q1 2020. On the other hand, in the US, about 40% of electricity was generated by gas, while in the European Union, around 40% was supplied by renewables [2].

Due to high electricity prices and high penetration of Distributed Energy Resources (DER), some consumers utilize Photovoltaic (PV) systems to provide their homes with electricity. Thus, ordinary consumers who can produce and consume electricity become prosumers. When a prosumer produces more electricity than it needs to cover its demand, excess energy is sold to the utility grid at a lower price compared with the buying price at which ordinary consumers within a neighboring area buy energy from the utility grid.

With recent advancements in Information and Communication Technologies (ICT) and massive deployment of DER, the concept of a microgrid has emerged as an alternative solution for coordinating local groups of prosumers. Microgrids bring the possibilities to increase efficient electricity utilization, which leads a reduced amount of energy imported from the utility grid. To achieve this, prosumers must be motivated to share energy with each other in the microgrid. Thus, pricing is one of the most important mechanisms for motivating prosumers to interact with each other in the microgrid.

Some works [3,4] have approached pricing formation in the microgrid in terms of optimizing prosumers' behavior, which is possible but unlikely in the real-world scenario. Due to the random prosumers' behavior, it becomes challenging to design a pricing model that motivates prosumers to share energy with each other and contributes to a decrease in energy imported from the utility grid. A new pricing model should provide more beneficial buying and selling prices of

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energy compared with the utility grid that will motivate prosumers not to sell excess energy to the utility grid and buy energy from the microgrid. Thus, the energy produced in the microgrid can be utilized more efficiently, which in turn will contribute to the reduction in the demand from the utility grid.

By extending our previous work [5], this paper proposes a novel dynamic pricing model for a microgrid of prosumers, which is able to provide lower buying and higher selling prices for electricity compared to the utility grid that decreases the demand from the utility grid, as well as allows to reduce the energy usage cost for a prosumer.

The main contributions of this paper are as follows:

- A novel dynamic pricing model that focuses on maximizing the utilization of energy produced in the microgrid is proposed. In addition, the paper demonstrates how to determine the amount of energy each prosumer can buy and sell by interacting with the microgrid.
- A mechanism to determine the energy usage cost based on the prosumer's contribution to the total level of energy consumption is proposed. In addition, a technique is developed to determine the profit from selling energy based on the prosumer's contribution to the total level of energy production.
- A mechanism to calculate penalties based on the prosumers' contribution to the total absolute deviation from the predicted level of total energy consumption or production is introduced.

The remainder of this paper is organized as follows. The literature review is presented in Section 2. The methodology and a novel dynamic pricing model for a microgrid of prosumers are presented in Section 3. Simulation results and discussion are presented in Section 4. Sensitivity analysis of the proposed pricing model is presented in Section 5. Finally, the conclusion is given in Section 6.

2. Literature review

A large number of game theory-based Peer-to-Peer (P2P) energy trading schemes have been proposed. A P2P energy trading system for a clustered microgrid is proposed in [6]. Multi-objective game-theoretic optimization is applied to find the most suitable sizes of the players and optimized payoff values. Alhasnawi et al. [7], has proposed a consensus algorithm-based coalition game-theoretic approach for multi-agent smart microgrids to minimize energy mismatching, energy bill, and load energy waste. Ullah et al. [8] has proposed a two-level Peer-to-Peer-to-Grid energy management framework. To minimize the prosumers' total operational costs, a Distribution Locational Marginal Price (DLMP) solution with Alternating Direction Method of Multipliers (ADMM) is designed. Prosumers trade energy with the utility grid based on the DLMP pricing signals, whereas a game-theoretic model is used when prosumers trade energy with each other. In [9], a novel scheme for P2P energy trading in a smart grid has been proposed. When demand matches supply, both selling and buying prices of energy are set according to the mid-market rate, which may lead to a higher buying price of energy in the microgrid compared with the utility grid. A novel model for real-time P2P energy trading in a community microgrid has been proposed in [3], where game theory is used to model the interactions among prosumers. A two-stage bidding strategy for P2P energy market has been proposed in [10] to enhance the utilization of local renewable energy. Prosumers can adjust the energy quantities before trading, which requires constant involvement of the end-user.

Constrained optimization is another popular technique to design P2P energy trading schemes. A near-optimal algorithm, named Energy Cost Optimization via Trade (ECO-Trade), for P2P energy trading among the smart homes in a microgrid has been proposed in [11]. An unfair cost distribution problem is addressed by assuring Pareto optimality among the prosumers. To maximize the renewable energy consumption, He et al. [12] has proposed a P2P energy trading scheme for a community sharing market, where the interactions between participants are modeled as by a leader-follower framework. To incentivize users to participate in the energy sharing, a novel dynamic pricing mechanism is developed, whereas prosumers and consumers are assumed to adjust their energy consumption. Mehdinejad et al. [13] has proposed a novel energy market, where prosumers and retailers can trade energy among each other. Each consumer can buy energy from local prosumers or retailers, whereas each prosumer has the right to sell energy to local consumers or retailers. It is challenging to achieve the effective utilization of the energy generated in the local area since prosumers and consumers have the right to choose a party to trade energy with. A market-clearing mechanism for smart grid has been proposed in [14]. The P2P energy trading is formulated as a social welfare maximization problem taking into account energy losses and network utilization fees. Alskaif et al. [15], has proposed a fully P2P energy trading model for Residential Energy Systems to minimize the overall cost for all households. To determine the bilateral trading preferences of prosumers, two strategies are proposed, where the first one is based on matching between energy demand and supply of participants, whereas, the second one is based on the distance between the households. Liu et al. [16], has proposed a P2P energy trading platform for residential houses to coordinate Demand Response (DR) schemes in the hour-ahead market.

In addition to the works mentioned above, auction theory is also used to model P2P energy trading markets. In [17], an integrated model has been proposed for P2P multi-energy sharing for Home Microgrids (HMGs). To achieve the optimal coordination of energy and heat systems in each HMGs, a double auction-based multi-energy sharing mechanism is developed. Xu et al. [18] has proposed a novel iterative uniform-price auction mechanism for P2P energy trading in a microgrid. Prosumers iteratively adjust their bids to determine the trading price, whereas an auction is used to match surplus and deficit among seller and buyer prosumers. Haggi et al. [19], has proposed a framework for P2P energy trading in active distribution networks using a combination of a multi-round double auction and an average pricing mechanism, where excess energy may be sold to the utility grid because the agreement has not been reached during negotiation, which leads to inefficient energy utilization in the microgrid. A double auction-based energy trading mechanism for a community sharing market consisting of prosumers and consumers has been proposed in [20]. A non-cooperative game is applied to determine the final equilibrium spot price. Yu et al. [21], has proposed a continuous group-wise double auction scheme to coordinate energy transactions among prosumers in a distribution-level market. Table 1 presents an overview of the existing approaches. Most of the proposed approaches assume that the end-user is available most of the time to participate in an auction or for the adjustment of its energy consumption, whereas the proposed pricing model does not depend on the user's availability. Application of the proposed models may lead to the case when two prosumers consume the same amount of energy, but the energy usage costs will be different. Although it is possible to reduce the demand from the utility grid by the excess energy in the microgrid, it is not always the case because sometimes prosumers cannot negotiate or cannot win an auction, and they have to interact with the utility grid, which leads to inefficient energy utilization in the microgrid.

3. Methodology

In this section, a novel dynamic pricing model for a microgrid of prosumers with photovoltaic systems is proposed.

Table 1
An overview of the existing approaches.

Authors	Objectives	Methods
Paudel et al. [3]	To develop an algorithm for P2P energy trading	Game theory
Anoh et al. [4]	To optimize energy trading costs in a single virtual microgrid	Game theory
Ali et al. [6]	To design the most efficient and economic microgrid system	Game theory, multi-objective game-theoretic optimization
Alhasnawi et al. [7]	To minimize the energy cost, energy waste, and power mismatching	A consensus algorithm based coalition game theory
Ullah et al. [8]	To efficiently manage the prosumers through proper incentive mechanism while securely managing the distribution networks	Game theory, optimization methods
Tushar et al. [9]	To optimize the economic benefits with fair competition and increase the market social welfare	Game theory
Zhang et al. [10]	To enhance the utilization of local renewable energy	Game theory, optimization methods
Alam et al. [11]	To maximize the total benefits of all participating households	Pareto optimality, optimization methods, Mixed Integer Linear Programming
He et al. [12]	To increase both stakeholders' revenue and market participants' utilities	Dynamic pricing, machine learning (Q-learning)
Mehdinejad et al. [13]	To maximize local players' social welfare and retailers' revenue	Primal–dual sub-gradient algorithm
Paudel et al. [14]	To design a proper market clearing mechanism for P2P energy trading while maintaining privacy	Optimization methods (social welfare maximization problem)
Alskaif et al. [15]	To maximize the utilization of locally produced energy, and to minimize the overall costs in the network for all households	Blockchain, smart contract, optimization methods
Liu et al. [16]	To coordinate DR schemes and level OFF potential generation/consumption disturbances in the hour-ahead context	Double-auction mechanism
Li et al. [17]	To achieve the coordination of the intelligent, self-interested, and privacy-conscious home microgrids, and conduct the electricity sharing and heat sharing simultaneously	Double-auction mechanism, model-driven optimization and data-driven prediction
Xu et al. [18]	To determine an efficient energy allocation, and to maximize economic benefits of prosumers	Auction mechanism
Haggi et al. [19]	To minimize the generation cost of utility-operated distributed generators, and the cost of purchasing power from the grid	Multi-round double auction, average pricing mechanism integrated with distributional locational marginal price
He et al. [20]	To increase the economic efficiency of the community, and to reduce the total electricity cost	Double-auction mechanism, game theory, machine learning
Yu et al. [21]	To coordinate the prosumers' energy dispatch, enable energy trading among prosumers, and maximize the overall social welfare in a local distribution area	Continuous group-wise double auction mechanism
Liu et al. [22]	To make the energy sharing among neighboring PV prosumers in the microgrid more economical	Bi-level programming model
Yahaya et al. [23]	To minimize electricity costs, ensure privacy and security	Private Ethereum blockchain, smart contract
Rasheed et al. [24]	To provide maximum comfort along with minimum cost	Optimization methods

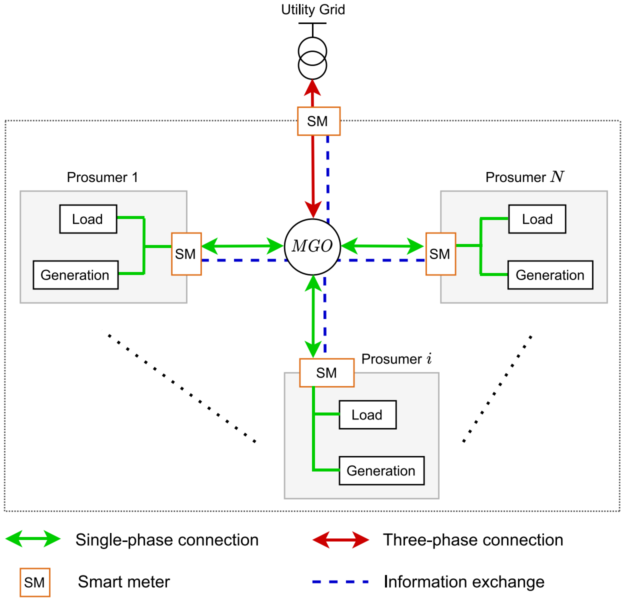

Fig. 1. System model of a microgrid of prosumers.

3.1. System model

Fig. 1 shows the structure of a microgrid consisting of N prosumers. Each end-user is expected to consume (buy) and produce (sell) energy. Thereby all end-users in a microgrid can be represented as prosumers, whereas the only difference between them is the energy usage profiles. Prosumers are connected to the Microgrid Operator (MGO) using a single-phase electricity connection, whereas the electricity connection between the MGO and the utility grid is three-phase. It should be noted that the type of the connection does not affect the overall performance of the proposed pricing model. However, the relevant assumption is that the connection between the households and the MGO is limited to 4 kW, which is a level of electricity consumption for a typical household. Thus, the MGO operates as an aggregator, which means all prosumers can sell excess energy to the MGO and buy the shortage from the MGO. All prosumers communicate with the MGO through a bidirectional communication channel, which is mainly used to submit energy usage data to the MGO. A smart meter, which is deployed at each prosumer, measures the amount of energy produced and consumed and sends the corresponding information to the MGO. In turn, the MGO aggregates energy usage data and then calculates the cost of electricity used for each prosumer.

In the proposed model, it is assumed that there is a MGO located within a microgrid that aggregates and dispatches energy within the

Table 2
Summary of symbols and notations.

Notation	Definition	Notation	Definition
n	Index of a prosumer	$\psi^{QD}_{n_h}$	Difference between the costs of buying energy from the utility grid and microgrid for a prosumer n in a time slot h
N	Total number of prosumers		
h	Index of a time slot	$\xi^{QD}_{n_h}$	Penalty that is added to the initial energy usage cost for a prosumer n in a time slot h
H	Total number of time slots		
$QD_{P_{n_h}}$	Predicted level of energy consumption for a prosumer n in a time slot h	$C^{F}_{n_h}$	Total energy usage cost for a prosumer n in a time slot h
$QD_{R_{n_h}}$	Actual level of energy consumption for a prosumer n in a time slot h	$P^{B}_{n_h}$	Initial profit from selling energy for a prosumer n in a time slot h
$QS_{P_{n_h}}$	Predicted level of energy production for a prosumer n in a time slot h	$\gamma^{QS}_{n_h}$	Absolute deviation from the predicted level of energy production of a prosumer n in a time slot h
$QS_{R_{n_h}}$	Actual level of energy production for a prosumer n in a time slot h	Γ^{QS}_{h}	Total absolute deviation from the predicted level of total energy production in a time slot h
λ_{b_h}	Buying price of energy from the utility grid in a time slot h	$\Delta^{QS}_{n_h}$	Prosumer's contribution to the total absolute deviation from the predicted level of total energy production in a time slot h
λ_{s_h}	Selling price of energy to the utility grid in a time slot h	$\psi^{QS}_{n_h}$	Difference between the profits from selling energy to the microgrid and utility grid for a prosumer n in a time slot h
λ_{e_h}	Internal equilibrium price for buying and selling energy in the microgrid in a time slot h	$\xi^{QS}_{n_h}$	Penalty that is subtracted from the initial profit for a prosumer n in a time slot h
$QD^{T}_{R_h}$	Total shortage of energy in the microgrid in a time slot h	$P^{F}_{n_h}$	Total profit from selling energy for a prosumer n in a time slot h
QS^{T}_{h}	Total excess energy available in the microgrid after self-consumption in a time slot h	$\mu^{MG}_{n_h}$	Part of the energy produced by a prosumer n in a time slot h, which is sold to the microgrid
SDR_h	Supply and demand ratio in a time slot h	$\mu^{UG}_{n_h}$	Part of the energy produced by a prosumer n in a time slot h, which is sold to the utility grid
$C^{B}_{n_h}$	Initial energy usage cost for a prosumer n in a time slot h	$\omega^{MG}_{n_h}$	Part of the energy consumed by a prosumer n in a time slot h, which is bought from the microgrid
$\gamma^{QD}_{n_h}$	Absolute deviation from the predicted level of energy consumption for a prosumer n in a time slot h	$\omega^{UG}_{n_h}$	Part of the energy consumed by a prosumer n in a time slot h, which is bought from the utility grid
Γ^{QD}_{h}	Total absolute deviation from the predicted level of total energy consumption in a time slot h	$Pr^{B}_{n_h}$	Actual buying price of energy from the microgrid for a prosumer n in a time slot h
$\Delta^{QD}_{n_h}$	Prosumer's contribution to the total absolute deviation from the predicted level of total energy consumption in a time slot h	$Pr^{S}_{n_h}$	Actual selling price of energy to the microgrid for a prosumer n in a time slot h
ρ	Resistance of a wire for a single-phase electricity connection	$\tau^{L}_{n_h}$	Cost to be paid by a prosumer n in a time slot h to cover the losses
V	Voltage in a single-phase electricity connection	k_L	Energy transfer loss coefficient
NP_{n_h}	Net power for a prosumer n in a time slot h	L_{n_h}	Energy transfer loss during the transmission of energy between a prosumer n and the MGO
$L^{s}_{n_h}$	Energy transfer loss for a prosumer (producer) n in a time slot h	$L^{b}_{n_h}$	Energy transfer loss for a prosumer (consumer) n in a time slot h
$L^{s}_{T_h}$	Total energy transfer loss for all producers in a time slot h	$L^{b}_{T_h}$	Total energy transfer loss for all consumers in a time slot h
L^{T}_{h}	Total energy transfer loss in a time slot h	QD^{UG}_{h}	Amount of energy has to be bought from the utility grid to cover the losses
C_{L_h}	Cost of buying energy from the utility grid to cover the losses	λ_{L_h}	Price of exchanging 1 kW of energy with the MGO for a prosumer in a time slot h
d	Distance between a prosumer and the MGO		

renewable energy community (a microgrid). First, the energy consumption and production profiles are predicted for all participants in a microgrid, which gives the information on total energy consumption and production in a particular time slot. Thus, the MGO provides an independent aggregator [25] with the information whether it will require some energy to be supplied to the microgrid or whether it will be able to supply some energy to the aggregator in a particular time slot. The MGO, which is an aggregator itself, may exchange energy with other aggregators outside the microgrid according to the EU regulations [26].

It should be emphasized that in this paper, the interaction with the utility grid and the terms import/export and buy/sell from the utility grid are considered from an economic point of view only. For instance, import from the utility grid means electricity was bought at the utility grid's selling price. The same applies to export to the utility grid. Whereas the interaction with the microgrid means that the prosumer buys/sells at the microgrid's prices. It should be noted that irrespective of whether the electricity is bought/sold from/into the utility grid or the microgrid, for the same demand and generation profiles the physical energy flow remains the same.

The main aim of this work is to design a pricing model for a microgrid of prosumers. All other aspects, including smart meters operation, communication between prosumers and the MGO are beyond the scope of this work. The notations used in this paper are summarized in Table 2.

In this work, a microgrid consists of N prosumers. Let $\mathcal{N} = \{1, 2, 3, \dots, N\}$ denote the set of prosumers in the microgrid, where n is the prosumer index and $n \in \mathcal{N}$, whereas, the total number of prosumers is given by $N \triangleq |\mathcal{N}|$. Energy usage cost for all prosumers is calculated at the end of a time slot, where each time slot is of one hour. Let $\mathcal{H} = \{1, 2, 3, \dots, H\}$ denote the set of all time slots, where h is the time slot index and $h \in \mathcal{H}$, whereas, the total number of time slots is given by $H \triangleq |\mathcal{H}| = 24$. Let QD_{P_n} denote the predicted energy consumption profile for a prosumer n for one day, and it is defined as follows:

$$QD_{P_n} = \{QD_{P_{n_1}}, QD_{P_{n_2}}, \dots, QD_{P_{n_H}}\}, \quad n \in \mathcal{N} \tag{1}$$

where $QD_{P_{n_h}}$ is the predicted level of energy consumption for a prosumer n in a time slot h and $QD_{P_{n_h}} \in QD_{P_n}$. Let QS_{P_n} denote the predicted energy production profile for a prosumer n for one day, and it is defined as follows:

$$QS_{P_n} = \{QS_{P_{n_1}}, QS_{P_{n_2}}, \dots, QS_{P_{n_H}}\}, \quad n \in \mathcal{N} \tag{2}$$

where $QS_{P_{n_h}}$ is the predicted level of energy production for a prosumer n in a time slot h and $QS_{P_{n_h}} \in QS_{P_n}$. Smart meters may submit the prosumers' energy usage data to the MGO at different time intervals (5 min/10 min/15 min). Let QD_{R_n} denote the actual energy consumption profile for a prosumer n for one day, and it is defined as follows:

$$QD_{R_n} = \{QD_{R_{n_1}}, QD_{R_{n_2}}, \ldots, QD_{R_{n_H}}\}, \quad n \in \mathcal{N} \tag{3}$$

where $QD_{R_{n_h}}$ is the actual level of energy consumption for a prosumer n in a time slot h and $QD_{R_{n_h}} \in QD_{R_n}$. Let QS_{R_n} denote the actual energy production profile for a prosumer n for one day, and it is defined as follows:

$$QS_{R_n} = \{QS_{R_{n_1}}, QS_{R_{n_2}}, \ldots, QS_{R_{n_H}}\}, \quad n \in \mathcal{N} \tag{4}$$

where $QS_{R_{n_h}}$ is the actual level of energy production for a prosumer n in a time slot h and $QS_{R_{n_h}} \in QS_{R_n}$. It should be noted that the prosumers' energy usage profiles are not the same, rather they are selected randomly from publicly available datasets [27,28], which is discussed in details in Section 4.

The first priority for prosumers is self-consumption; thus, each prosumer consumes its own PV energy to cover its demand. If there is not enough PV energy produced on the prosumer's side, the rest is bought from the MGO. On the other hand, if a prosumer can cover its demand by consuming its own PV energy and has excess energy to share, the surplus is sold to the MGO. Let NP_{n_h} denote the net power for a prosumer n in a time slot h, and it is defined as follows:

$$NP_{n_h} = QS_{R_{n_h}} - QD_{R_{n_h}} \tag{5}$$

Let QS_h^T denote the total excess energy that is available in a microgrid after self-consumption in a time slot h, and it is calculated as follows:

$$QS_h^T = \sum_{n=1}^{N} NP_{n_h}, \quad NP_{n_h} > 0 \tag{6}$$

Let QD_h^T denote the total shortage of energy in a microgrid after self-consumption in a time slot h, and it is calculated as follows:

$$QD_h^T = \sum_{n=1}^{N} |NP_{n_h}|, \quad NP_{n_h} < 0 \tag{7}$$

After self-consumption, if the total shortage of energy is greater than the total excess energy, the rest is bought (imported) from the utility grid. On the other hand, excess energy is sold (exported) to the utility grid. Hence, the state of the microgrid can be identified as the ratio of the total excess energy to the total shortage of energy. Let SDR_h denote the Supply and Demand Ratio (*SDR*) in a time slot h. Combining (6) and (7), *SDR* in a time slot h is calculated as follows:

$$SDR_h = \frac{QS_h^T}{QD_h^T}, \quad \text{where} \quad QD_h^T > 0 \tag{8}$$

Thus, when $SDR_h = 1$, the microgrid is in the state "Standalone", and there is no interaction with the utility grid. If $SDR_h > 1$, the microgrid operates in the state "Seller", which means that excess energy is sold to the utility grid. On the other hand, when $SDR_h < 1$, the microgrid operates in the state "Buyer", and the shortage is bought from the utility grid. The case when there is no demand ($QD_h^T = 0$) and all the produced energy in the microgrid is sold to the utility grid is not considered in this work; thus, in (8), the only case when $QD_h^T > 0$ is considered.

In this work, the energy transfer loss is taken into account. Fig. 2 shows that in each time slot prosumers are divided into two categories, namely producers and consumers. During the transfer of energy from a producer to a consumer (between prosumers), the energy transfer loss is unavoidable. For simplicity, all the prosumers are located on the same distance from the MGO, which is defined as d. Moreover, all prosumers are connected to the MGO using a single-phase electricity connection and the same type of wire, the resistance of which is defined as ρ. Let k_L denote the energy transfer loss coefficient, and it is calculated as follows:

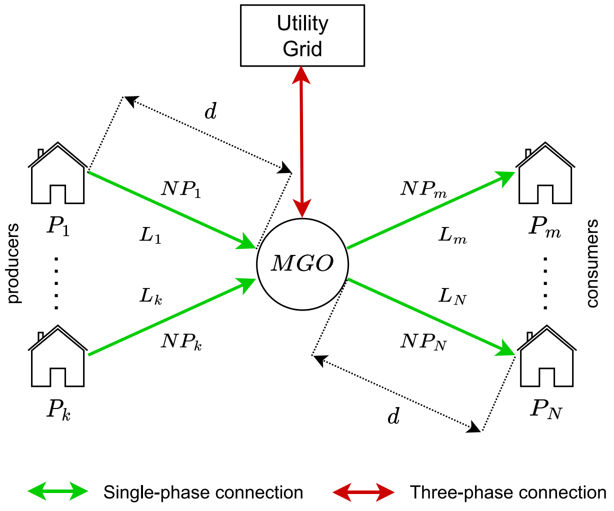

Fig. 2. Energy transfer loss model.

$$k_L = \frac{\rho * d}{V} \tag{9}$$

Let L_{n_h} denote the energy transfer loss during the transfer of energy (NP_{n_h}) between a prosumer n and the MGO in a time slot h, and it is calculated as follows:

$$L_{n_h} = k_L * NP_{n_h}^2 \tag{10}$$

Let λ_b denote the buying price of energy from the utility grid, whereas, λ_s denote the selling price of energy to the utility grid. However, the prices λ_b, λ_s may vary over time. Let Λ_b denote the set of buying prices of energy from the utility grid for one day, and it is defined as follows:

$$\Lambda_b = \{\lambda_{b_1}, \lambda_{b_2}, \lambda_{b_3}, \ldots, \lambda_{b_h}\} \tag{11}$$

where λ_{b_h} is the buying price of energy from the utility grid in a time slot h and $\lambda_{b_h} \in \Lambda_b$. Let Λ_s denote the set of selling prices of energy to the utility grid for one day, and it is defined as follows:

$$\Lambda_s = \{\lambda_{s_1}, \lambda_{s_2}, \lambda_{s_3}, \ldots, \lambda_{s_h}\} \tag{12}$$

where λ_{s_h} is the selling price of energy to the utility grid in a time slot h and $\lambda_{s_h} \in \Lambda_s$.

The overall methodology of the proposed approach is as follows. Smart meters measure the energy consumption and production of a prosumer and send energy usage data to the MGO at a time interval that is equal to one hour in this work, whereas the predicted energy usage profiles for all prosumers are predicted by the MGO. At the end of each hour, the MGO aggregates energy usage data sent by prosumers to calculate the supply and demand ratio (SDR_h). Furthermore, the process of calculating the energy usage cost and profit for all prosumers is based on the MGO's side.

3.2. Assumptions

There are six major assumptions in this work: (i) To simplify the energy transfer loss calculation and allocation, the distance between any prosumer and the MGO is taken as a constant, which is equal to 100 m ($d = 100$ m). (ii) The energy transfer loss when interacting with the utility grid is not considered, as these losses have already been accounted for in the utility grid's prices. (iii) All prosumers are connected to the MGO using a single-phase electricity connection with the same type of wire; thus, the electrical wire resistance (ρ) is the same for all single-phase connections ($\rho = 0.01$ Ohm/m) between prosumers and the MGO. (iv) The MGO predicts energy usage profiles for each prosumer n for each time slot h. Although an energy usage forecasting mechanism is beyond the scope of this paper, the dependency of the prosumer's energy usage cost on its absolute deviation from the predicted energy consumption is analyzed in Section 5. (v) Since the data aggregation mechanism is beyond the scope of this paper, it is assumed that energy usage data of each prosumer n are received from smart meters and aggregated at the MGO during each time slot h, so that actual energy usage profiles of all prosumers are available at the end of each time slot. (vi) There is a continuous supply of energy from the utility grid so that the shortage can be bought from the utility grid at any time, as well as excess energy can be sold to the utility grid at any time.

3.3. Pricing model

In this section, a novel pricing model for the microgrid is proposed to reduce the energy usage cost for all prosumers and to increase the profit from selling energy, which increases efficient energy utilization in the microgrid and contributes to the reduction in the demand from the utility grid. Instead of selling energy to the utility grid, excess energy can be utilized in the microgrid to cover some part of the microgrid's demand. Hence, it is important to motivate as many prosumers as possible to interact with each other in the microgrid. To motivate prosumers, the total energy usage cost for each prosumer in the microgrid should be less than or equal to the cost of buying energy from the utility grid. In an ideal scenario, namely when demand matches supply i.e. $SDR_h = 1$, there is no need to interact with the utility grid, and all the energy is sold and bought in the microgrid at the same price. Thus, instead of defining both internal buying and selling prices in the microgrid [22], only one internal price is used.

3.3.1. Equilibrium price

Initially, the price, at which the energy is sold and bought in the microgrid is called an equilibrium price that is calculated based on the *SDR* [22,23]. In case when $QD_h^T = 0$, there is no demand in the microgrid and all excess energy produced by prosumers (QS_h^T) is sold to the utility grid at a price λ_{s_h}. It should be noted that there could also be a case when $QS_h^T = 0$ and $QD_h^T \approx 0$ simultaneously, which means that all prosumers cover their demand by their own PV energy or there is no demand at all, as well as there is no excess energy to share. In case when $SDR_h = 0$, it means that there is no excess energy in the microgrid and energy required to cover the demand of the microgrid is bought from the utility grid at a price λ_{b_h}. When $SDR_h > 1$, it means that there is enough excess energy to cover the demand in the microgrid, as well as to sell some part to the utility grid at a price λ_{s_h}. The most challenging case is when $SDR_h = 1$, namely the total excess energy is equal to the total shortage of energy ($QS_h^T = QD_h^T$). Prosumers may decide the price they agree with in advance, or it may be set by the MGO. To ensure the lowest buying price in the microgrid, the selling price of energy to the utility grid is used as the internal equilibrium price in this scenario. Moreover, when $0 < SDR_h < 1$, it means that there is not enough excess energy to cover the demand in the microgrid and the shortage is bought from the utility grid at a price λ_{b_h}.

In [22], internal buying and selling prices are not the same, whereas in the proposed approach, the equilibrium price is represented by a collapse of two curves (gray curves) to a single line (red line) (Fig. 3). It should be noted that the final price for a prosumer may be changed (increased or decreased) due to the penalties added, as well as the cost to cover the energy transfer loss, which is discussed further in this section.

Thus, the internal equilibrium price depends on SDR_h and is calculated according to the formula of a straight line passing through two points. The first point is (0; λ_{b_h}), namely when $SDR_h = 0$, and the shortage is bought from the utility grid at a price λ_{b_h}. The second point is (1; λ_{s_h}), and it represents the case when $SDR_h = 1$, and excess energy is sold to the utility grid at a price λ_{s_h} (Fig. 3). Let λ_{e_h} denote the internal equilibrium price in a time slot h, which is calculated as follows:

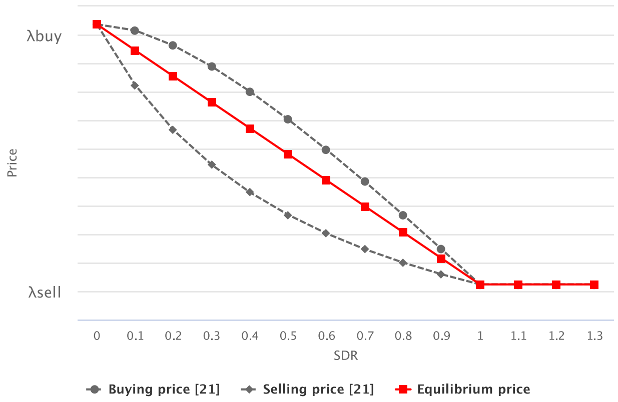

Fig. 3. An internal equilibrium price.

$$\lambda_{e_h} = SDR_h * (\lambda_{s_h} - \lambda_{b_h}) + \lambda_{b_h} \tag{13}$$

3.3.2. Pricing model

It is highly unlikely that a prosumer's energy usage profile can be accurately predicted in a real-world scenario [16]; thus, there always will be a difference between predicted and actual energy usage profiles. In this work, the MGO is responsible for predicting the energy usage profiles for all prosumers in a microgrid. The proposed approach focuses on determining the energy usage cost and profit from selling energy and not on determining a particular buying or selling price of energy. In other words, prosumers' behavior is considered as random, whereas, the energy usage cost for a prosumer is calculated taking into account a possible absolute deviation from the predicted level of energy consumption. The profit from selling energy for a prosumer is calculated taking into account a possible absolute deviation from the predicted level of energy production. The absolute value of the prosumer's deviation is used to understand what the prosumer's contribution to the total absolute deviation is. It does not matter whether a prosumer's actual value of electricity consumption (production) is increased or decreased compared to the predicted one. In other words, a prosumer will be penalized in both scenarios. This is due to the fact that the microgrid operator sends the information on the predicted energy consumption (production) to an independent aggregator. This means that the amount of energy to be supplied from the independent aggregator to the microgrid is identified in advance based on the prediction. If we define the total deviation as the difference between the Real Consumption and Predicted Consumption (without the absolute value), then that the larger the number of prosumers the smaller is the total deviation. Next, the three most common microgrid's scenarios are explained.

3.3.3. Scenario 1: The total excess energy is equal to the total shortage of energy

In this scenario, the total shortage of energy (QD_h^T) is equal to the total excess energy (QS_h^T) in the microgrid in a time slot h ($SDR_h = 1$). All energy is sold and bought in the microgrid, and there is no need to interact with the utility grid until the demand including the energy transfer loss does not exceed the excess energy. Let $C_{n_h}^B$ denote the initial cost of buying energy from the microgrid for a prosumer n in a time slot h, which is calculated as follows:

$$C_{n_h}^B = QD_{R_{n_h}} * \lambda_{e_h} \tag{14}$$

In case when two prosumers consumed the same amount of energy, while one of them did not follow its predicted level of energy consumption, then the energy usage costs will not be the same for these prosumers. Let $\gamma_{n_h}^{QD}$ denote the absolute deviation from the predicted energy consumption profile of a prosumer n in a time slot h, which is calculated as follows:

$$\gamma_{n_h}^{QD} = \left| QD_{R_{n_h}} - QD_{P_{n_h}} \right|, \quad \text{where} \quad QD_{R_{n_h}} > 0 \tag{15}$$

Prosumers cannot be charged if they do not consume energy in a time slot h; thus, in (15), an absolute deviation is only calculated for prosumers with non-zero consumption. Prosumers are penalized by adding a penalty to the initial cost ($C_{n_h}^{B}$) based on the prosumer's contribution to the total absolute deviation from the predicted level of total energy consumption. Hence, more a prosumer deviates from the predicted energy consumption profile, the greater the penalty. Let Γ_h^{QD} denote the total absolute deviation from the predicted level of total energy consumption in a time slot h, which is calculated as follows:

$$\Gamma_h^{QD} = \sum_{n=1}^{N} \gamma_{n_h}^{QD} \tag{16}$$

Let $\Delta_{n_h}^{QD}$ denote the prosumer's contribution to the total absolute deviation from the predicted level of total energy consumption in a time slot h. Combining (15) and (16), $\Delta_{n_h}^{QD}$ is calculated as follows:

$$\Delta_{n_h}^{QD} = \frac{\gamma_{n_h}^{QD}}{\Gamma_h^{QD}}, \quad \text{where} \quad \Gamma_h^{QD} > 0 \tag{17}$$

If prosumers do not deviate from the predicted energy consumption profiles, the total absolute deviation will be equal to 0 ($\Gamma_h^{QD} = 0$), and there is no point in calculating prosumer's contribution because it will be equal to 0; thus, in (17), the prosumer's contribution is only calculated for the case when at least one prosumer deviates from its predicted energy consumption profile. If $\Gamma_h^{QD} \approx 0$, which means that all prosumers followed predicted energy consumption profiles, the total cost for a prosumer n in a time slot h is calculated according to (14). To motivate a prosumer not to deviate from the predicted energy consumption profile, a penalty is added to the initial cost. On the other hand, to be able to provide a lower buying price of energy in the microgrid compared with the utility grid, the total cost for a prosumer cannot exceed the baseline cost (cost of buying energy from the utility grid). Let $C_{n_h}^{UG}$ denote the baseline cost for a prosumer n in a time slot h, which is calculated as follows:

$$C_{n_h}^{UG} = QD_{R_{n_h}} * \lambda_{b_h} \tag{18}$$

Let $C_{n_h}^{F}$ denote the total cost of buying energy from the microgrid for a prosumer n in a time slot h, which is subject to the constraint:

$$C_{n_h}^{F} \leq C_{n_h}^{UG} \tag{19}$$

More precisely, no fixed value can be added to the initial cost because the total cost may exceed the baseline cost. Let $\xi_{n_h}^{QD}$ denote a penalty that is added to the initial cost for a prosumer n in a time slot h, which is subject to the constraint:

$$\xi_{n_h}^{QD} \leq C_{n_h}^{UG} - C_{n_h}^{B} \tag{20}$$

In this work, the difference between the baseline cost ($C_{n_h}^{UG}$) and the initial cost ($C_{n_h}^{B}$) is considered as the starting point for calculating a penalty. Let $\psi_{n_h}^{QD}$ denote the difference between the baseline and initial costs for a prosumer n in a time slot h, which is calculated as follows:

$$\psi_{n_h}^{QD} = C_{n_h}^{UG} - C_{n_h}^{B} \tag{21}$$

The difference between the baseline and initial costs ($\psi_{n_h}^{QD}$) cannot be used as a penalty because it will lead to the case when the total cost ($C_{n_h}^{F}$) equals to the baseline cost ($C_{n_h}^{UG}$). To ensure (19), only some part of $\psi_{n_h}^{QD}$ can be used as a penalty. Combining (17) and (21), the penalty for a prosumer n in a time slot h (when buying energy) is calculated as follows:

$$\xi_{n_h}^{QD} = \Delta_{n_h}^{QD} * \psi_{n_h}^{QD} \tag{22}$$

During the transfer of energy between a prosumer and the MGO, the energy transfer loss is unavoidable. Let $L_{n_h}^{s}$ denote the energy transfer loss for a prosumer n (producer) transferring NP_{n_h} amount of energy to the MGO in a time slot h, and it is calculated as follows:

$$L_{n_h}^{s} = NP_{n_h}^{2} * k_L, \quad NP_{n_h} > 0 \tag{23}$$

Let $L_{n_h}^{b}$ denote the energy transfer loss for a prosumer n (consumer) buying NP_{n_h} amount of energy from the MGO in a time slot h, and it is calculated as follows:

$$L_{n_h}^{b} = NP_{n_h}^{2} * k_L, \quad NP_{n_h} < 0 \tag{24}$$

Let $L_{T_h}^{s}$ denote the total energy transfer loss for all prosumers (producers) transferring energy to the MGO in a time slot h, and it is calculated as follows:

$$L_{T_h}^{s} = \sum_{n=1}^{N} L_{n_h}^{s} \tag{25}$$

Let $L_{T_h}^{b}$ denote the total energy transfer loss for all prosumers (consumers) buying energy from the MGO in a time slot h, and it is calculated as follows:

$$L_{T_h}^{b} = \sum_{n=1}^{N} L_{n_h}^{b} \tag{26}$$

Let L_h^{T} denote the total energy transfer loss in the microgrid in a time slot h, and it is calculated as follows:

$$L_h^{T} = L_{T_h}^{s} + L_{T_h}^{b} \tag{27}$$

Thus, the total excess energy available to share in the microgrid is decreased by $L_{T_h}^{s}$, whereas the total shortage of energy in the microgrid is increased by $L_{T_h}^{b}$. Let QD_h^{UG} denote the amount of energy has to be bought from the utility grid to cover the energy transfer losses in a time slot h, and it is calculated as follows:

$$QD_h^{UG} = L_{T_h}^{s} + L_{T_h}^{b} \tag{28}$$

The energy to cover the total energy transfer loss in the microgrid is bought from the utility grid at a price λ_{b_h}. Let C_{L_h} denote the cost of buying energy from the utility grid in a time slot h to cover the energy transfer losses in the microgrid (QD_h^{UG}), and it is calculated as follows:

$$C_{L_h} = QD_h^{UG} * \lambda_{b_h} \tag{29}$$

Thus, all prosumers exchanging energy with the MGO have to pay an additional cost to cover the cost of buying energy from the utility grid to cover the losses. Since all prosumers are located on the same distance from the MGO and the type of the wires is the same for all prosumers, the cost each prosumer has to pay is based on the amount of energy exchanged with the MGO. Let λ_{L_h} denote the price of exchanging 1 kW of energy with the MGO for a prosumer n in a time slot h, and it is calculated as follows:

$$\lambda_{L_h} = \frac{C_{L_h}}{L_h^{T}} \tag{30}$$

Let $\tau_{n_h}^{L}$ denote the cost that has to be paid by a prosumer n in a time slot h to cover the energy transfer losses, and it is calculated as follows:

$$\tau_{n_h}^{L} = \lambda_{L_h} * L_{n_h}^{b(s)} \tag{31}$$

It should be noted that in (31), the energy transfer loss for a prosumer n has a superscript $b(s)$ ($L_{n_h}^{b(s)}$), which means that the cost to cover the losses may be calculated using (31) for both producers (23) and consumers (24).

Finally, by combining (14), (22) and (31), the total cost of buying energy from the microgrid for a prosumer n in a time slot h is calculated as follows:

$$C^F_{n_h} = C^B_{n_h} + \xi^{QD}_{n_h} + \tau^L_{n_h} \tag{32}$$

Thus, the total energy usage cost for a prosumer n in a time slot h ($C^F_{n_h}$) consists of the initial cost ($C^B_{n_h}$), a penalty ($\xi^{QD}_{n_h}$) that depends on the prosumer's contribution to the total absolute deviation from the predicted level of total energy consumption, and the cost that has to be paid to cover the losses ($\tau^L_{n_h}$).

Let $P^B_{n_h}$ denote the initial profit from selling energy to the microgrid for a prosumer n in a time slot h, which is calculated as follows:

$$P^B_{n_h} = QS_{R_{n_h}} * \lambda_{e_h} \tag{33}$$

In case when two prosumers produced the same amount of energy, while one of them did not follow its predicted level of energy production, then the profits of selling energy will be different for these prosumers. Let $\gamma^{QS}_{n_h}$ denote the absolute deviation from the predicted energy production profile of a prosumer n in a time slot h, which is calculated as follows:

$$\gamma^{QS}_{n_h} = \left| QS_{R_{n_h}} - QS_{P_{n_h}} \right|, \quad \text{where} \quad QS_{R_{n_h}} > 0 \tag{34}$$

Prosumers cannot get any profit if they do not produce energy in a time slot h; thus, in (34), an absolute deviation is only calculated for prosumers with non-zero production. Prosumers are penalized by subtracting a penalty from the initial profit ($P^B_{n_h}$) based on the prosumer's contribution to the total absolute deviation from the predicted level of total energy production. Hence, the more a prosumer deviates from the predicted energy production profile, the greater the penalty. Let Γ^{QS}_h denote the total absolute deviation from the predicted level of total energy production in a time slot h, which is calculated as follows:

$$\Gamma^{QS}_h = \sum_{n=1}^{N} \gamma^{QS}_{n_h} \tag{35}$$

Let $\Delta^{QS}_{n_h}$ denote the prosumer's contribution to the total absolute deviation from the predicted level of total energy production in a time slot h. Combining (34) and (35), $\Delta^{QS}_{n_h}$ is calculated as follows:

$$\Delta^{QS}_{n_h} = \frac{\gamma^{QS}_{n_h}}{\Gamma^{QS}_h}, \quad \text{where} \quad \Gamma^{QS}_h > 0 \tag{36}$$

If prosumers do not deviate from the predicted energy production profiles, the total absolute deviation will be equal to 0 ($\Gamma^{QS}_h = 0$), which means that the contribution to the total absolute deviation will be equal to 0 for all prosumers; thus, in (36), the prosumer's contribution is only calculated for the case when at least one prosumer deviates from its predicted energy production profile. If $\Gamma^{QS}_h \approx 0$, which means that all prosumers followed predicted energy production profiles, the total profit for a prosumer n in a time slot h is calculated according to (33). To motivate a prosumer not to deviate from the predicted energy production profile, the initial profit is decreased by a penalty. On the other hand, to be able to provide a higher selling price of energy in the microgrid compared with the utility grid, the total profit for a prosumer cannot be less than the baseline profit (profit from selling energy to the utility grid). Let $P^{UG}_{n_h}$ denote the baseline profit for a prosumer n in a time slot h, which is calculated as follows:

$$P^{UG}_{n_h} = QS_{R_{n_h}} * \lambda_{s_h} \tag{37}$$

Let $P^F_{n_h}$ denote the total profit from selling energy to the microgrid for a prosumer n in a time slot h, which is subject to the constraint:

$$P^F_{n_h} \geq P^{UG}_{n_h} \tag{38}$$

The initial profit cannot be decreased by any fixed value because the total profit may become less than the baseline profit. Let $\xi^{QS}_{n_h}$ denote a penalty that is subtracted from the initial profit for a prosumer n in a time slot h, which is subject to the constraint:

$$\xi^{QS}_{n_h} \leq P^B_{n_h} - P^{UG}_{n_h} \tag{39}$$

Similar to (21), the difference between the initial and baseline profits is used to calculate a penalty. Let $\psi^{QS}_{n_h}$ denote the difference between the initial and baseline profits for a prosumer n in a time slot h, which is calculated as follows:

$$\psi^{QS}_{n_h} = P^B_{n_h} - P^{UG}_{n_h} \tag{40}$$

The difference between the initial and baseline profits ($\psi^{QS}_{n_h}$) cannot be used as a penalty because it will lead to the case when the total profit ($P^F_{n_h}$) equals to the baseline profit ($P^{UG}_{n_h}$). To ensure (38), only some part of $\psi^{QS}_{n_h}$ can be used as a penalty. Combining (36) and (40), the penalty for a prosumer n in a time slot h is calculated as follows:

$$\xi^{QS}_{n_h} = \Delta^{QS}_{n_h} * \psi^{QS}_{n_h} \tag{41}$$

Finally, by combining (33), (41), and (31), the total profit from selling energy to the microgrid for a prosumer n in a time slot h is calculated as follows:

$$P^F_{n_h} = P^B_{n_h} - \xi^{QS}_{n_h} - \tau^L_{n_h} \tag{42}$$

In this particular scenario, when $SDR_h = 1$, the prices of selling energy to the utility grid and to the microgrid in a time slot h are the same ($\lambda_{s_h} = \lambda_{e_h}$) according to (13), which means that there will be no penalties for prosumers when calculating the profit from selling energy. Even if some prosumers deviate from the predicted energy production profiles, the microgrid continues working in the standalone mode; thus, prosumers are not penalized for any changes in energy production profiles, and the total profit for a prosumer n in a time slot h consists of the initial profit ($P^B_{n_h}$) and the cost that has to be paid to cover the losses ($\tau^L_{n_h}$).

3.3.4. Scenario 2: The total excess energy is greater than the total shortage of energy

In this scenario, the total excess energy (QS^T_h) is greater than the total shortage of energy (QD^T_h) in the microgrid in a time slot h ($SDR_h > 1$). The total cost ($C^F_{n_h}$) of buying energy from the microgrid (except the cost that has to be paid to cover the energy transfer losses) for each prosumer n in a time slot h is calculated according to (32). The energy transfer losses may be covered by PV energy produced in the microgrid or by buying energy from the utility grid. If there is enough excess energy in the microgrid, the energy transfer losses are covered by the energy produced in the microgrid. On the other hand, if the energy transfer losses cannot be covered by the excess energy in the microgrid, the shortage is bought from the utility grid. Let QD^{UG}_h denote the amount of energy that has to be bought from the utility grid to cover the losses, and it is calculated as follows:

$$QD^{UG}_h = (QD^T_h + L^b_{T_h}) - (QS^T_h - L^s_{T_h}) \tag{43}$$

The price of exchanging 1 kW of energy with the MGO for a prosumer n in a time slot h is calculated as follows (taking into account (43)):

$$\lambda_{L_h} = \begin{cases} \dfrac{QD^{UG}_h * \lambda_{b_h}}{L^T_h}, & QD^{UG}_h > 0 \\[2ex] \dfrac{L^T_h * \lambda_{e_h}}{L^T_h}, & QD^{UG}_h < 0 \end{cases} \tag{44}$$

Taking into account (44), the cost that has to be paid by a prosumer n in a time slot h to cover the energy transfer losses is calculated according to (31).

The total profit ($P^F_{n_h}$) from selling energy to the microgrid is calculated in a different manner compared with (42). Consider a simple example. Let P_1, P_2 be the prosumers who only consume energy buying it from the microgrid, whereas the total energy consumed $QD^T_{R_h} = 4$ kW in a time slot h. Let P_3, P_4 be the prosumers who only produce energy and sell it to the microgrid, where both P_3 and P_4 produced the same amount of energy ($QS_{R_{3_h}} = QS_{R_{4_h}} = 4$ kW) in a time slot h. In this example, $SDR_h = 8/4 = 2$. If the total demand in the microgrid ($QD^T_{R_h} = 4$ kW) is covered by only energy produced by P_4 (4 kW), it will lead to the case when P_3 sells all the energy produced ($QS_{R_{3_h}}$) to the utility grid at a price λ_{s_h}, whereas, P_4 sells $QS_{R_{4_h}}$ (4 kW) to the microgrid at a price λ_{e_h} ($\lambda_{e_h} \geq \lambda_{s_h}$).

To eliminate such a scenario, each prosumer sells at least some part of the energy produced to the microgrid, whereas the rest is sold to the utility grid. Let $\mu^{MG}_{n_h}$ denote the part of the energy produced by a prosumer n in a time slot h, which is sold to the microgrid, and it is calculated as follows:

$$\mu^{MG}_{n_h} = QS_{R_{n_h}} * SDR^{-1}_h \tag{45}$$

Let $\mu^{UG}_{n_h}$ denote the part of the energy produced by a prosumer n in a time slot h, which is sold to the utility grid, and it is calculated as follows:

$$\mu^{UG}_{n_h} = QS_{R_{n_h}} * (1 - SDR^{-1}_h) \tag{46}$$

In this scenario, the initial profit consists of two parts, namely the profit from selling energy to the microgrid and the profit from selling energy to the utility grid. Thus, the initial profit for a prosumer n in a time slot h is calculated as follows:

$$P^B_{n_h} = \mu^{MG}_{n_h} * \lambda_{e_h} + \mu^{UG}_{n_h} * \lambda_{s_h} \tag{47}$$

To motivate a prosumer not to deviate from the predicted energy production profile, the initial profit is decreased by a penalty. It should be noted that the profit from selling energy to the utility grid cannot be decreased. Hence, it is only possible to decrease the profit from selling energy to the microgrid. Thus, taking into account (38), the penalty that is subtracted from the initial profit (47) is subject to the constraint:

$$\xi^{QS}_{n_h} \leq \mu^{MG}_{n_h} * \lambda_{e_h} - \mu^{MG}_{n_h} * \lambda_{s_h} \tag{48}$$

In this scenario, the difference between the profits is calculated only for the part of the energy that is sold to the microgrid ($\mu^{MG}_{n_h}$). Thus, the difference between the profits for a prosumer n in a time slot h is calculated as follows:

$$\psi^{QS}_{n_h} = \mu^{MG}_{n_h} * \lambda_{e_h} - \mu^{MG}_{n_h} * \lambda_{s_h} \tag{49}$$

The initial profit (47) is decreased depending on (36). Thus, combining (36) and (49), the penalty that is subtracted from the initial profit (47) is calculated as follows:

$$\xi^{QS}_{n_h} = \Delta^{QS}_{n_h} * \psi^{QS}_{n_h} \tag{50}$$

Combining (45), (46), (50), and (31) (taking into account (44)), the total profit from selling energy to the microgrid for a prosumer n in a time slot h is calculated as follows:

$$P^F_{n_h} = \mu^{MG}_{n_h} * \lambda_{e_h} + \mu^{UG}_{n_h} * \lambda_{s_h} - \xi^{QS}_{n_h} - \tau^L_{n_h} \tag{51}$$

3.3.5. *Scenario 3: The total excess energy is less than the total shortage of energy*

In this scenario, the total shortage of energy (QD^T_h) is greater than the total excess energy (QS^T_h) in the microgrid in a time slot h ($SDR_h < 1$). The total profit ($P^F_{n_h}$) from selling energy to the microgrid for each prosumer n in a time slot h is calculated according to (42). The total cost ($C^F_{n_h}$) of buying energy from the microgrid is calculated in a different manner compared with (32). Consider a simple example. Let P_1, P_2 be the prosumers who only produce energy and sell it to the microgrid, whereas the total energy produced $QS^T_{R_h} = 5$ kW in a time slot h. Let P_3, P_4 be the prosumers who only consume energy buying it from the microgrid, where both P_3 and P_4 consumed the same amount of energy ($QD_{R_{3_h}} = QD_{R_{4_h}} = 5$ kW) in a time slot h. In this example, $SDR_h = 5/10 = 1/2$. If all the energy produced in the microgrid ($QS^T_{R_h} = 5$ kW) is sold to P_3, it will lead to the case when P_3 covers the demand ($QD_{R_{3_h}} = 5$ kW) buying energy from the microgrid at a price λ_{e_h}, whereas, P_4 covers the demand ($QD_{R_{4_h}} = 5$ kW) buying energy from the utility grid at a price λ_{b_h} ($\lambda_{b_h} \geq \lambda_{e_h}$). To eliminate such a scenario, each prosumer covers at least some part of the demand by the energy produced in the microgrid, whereas the rest is bought from the utility grid.

Let $\omega^{MG}_{n_h}$ denote the part of the energy consumed by a prosumer n in a time slot h, which is bought from the microgrid, and it is calculated as follows:

$$\omega^{MG}_{n_h} = QD_{R_{n_h}} * SDR_h \tag{52}$$

Let $\omega^{UG}_{n_h}$ denote the part of the energy consumed by a prosumer n in a time slot h, which is bought from the utility grid, and it is calculated as follows:

$$\omega^{UG}_{n_h} = QD_{R_{n_h}} * (1 - SDR_h) \tag{53}$$

In this scenario, the initial cost consists of two parts, namely the cost of buying energy from the microgrid and the cost of buying energy from the utility grid. Thus, the initial cost for a prosumer n in a time slot h is calculated as follows:

$$C^B_{n_h} = \omega^{MG}_{n_h} * \lambda_{e_h} + \omega^{UG}_{n_h} * \lambda_{b_h} \tag{54}$$

To motivate a prosumer not to deviate from the predicted energy consumption profile, a penalty is added to the initial cost. It should be noted that the cost of buying energy from the utility grid cannot be increased. Hence, it is only possible to add a penalty to the cost of buying energy from the microgrid. Thus, taking into account (19), the penalty that is added to the initial cost (54) is subject to the constraint:

$$\xi^{QD}_{n_h} \leq \omega^{MG}_{n_h} * \lambda_{b_h} - \omega^{MG}_{n_h} * \lambda_{e_h} \tag{55}$$

In this scenario, the difference between the costs is calculated only for the part of the energy that is bought from the microgrid ($\omega^{MG}_{n_h}$). Thus, the difference between the costs for a prosumer n in a time slot h is calculated as follows:

$$\psi^{QD}_{n_h} = \omega^{MG}_{n_h} * \lambda_{b_h} - \omega^{MG}_{n_h} * \lambda_{e_h} \tag{56}$$

The initial cost (54) is increased depending on (17). Thus, combining (17) and (56), the penalty that is added to the initial cost (54) is calculated as follows:

$$\xi^{QD}_{n_h} = \Delta^{QD}_{n_h} * \psi^{QD}_{n_h} \tag{57}$$

Combining (52), (53), (57), and (31), the total cost of buying energy from the microgrid for a prosumer n in a time slot h is calculated as follows:

$$C^F_{n_h} = \omega^{MG}_{n_h} * \lambda_{e_h} + \omega^{UG}_{n_h} * \lambda_{b_h} + \xi^{QD}_{n_h} + \tau^L_{n_h} \tag{58}$$

By combining the methodologies of calculating the total cost and total profit for a prosumer in different microgrid scenarios, the total cost for a prosumer n in a time slot h is calculated according to the Algorithm 1, whereas, the total profit for a prosumer n in a time slot h is calculated according to the Algorithm 2.

Moreover, the actual price at which a prosumer n bought energy from the microgrid in a time slot h can be determined by dividing the total cost ($C^F_{n_h}$) by the amount of energy consumed ($QD_{R_{n_h}}$). Let $Pr^B_{n_h}$ denote the actual buying price of energy from the microgrid for a prosumer n in a time slot h, which is calculated as follows:

$$Pr^B_{n_h} = \frac{C^F_{n_h}}{QD_{R_{n_h}}}, \quad \text{where} \quad QD_{R_{n_h}} > 0 \tag{59}$$

In (59), the actual buying price can be calculated only for a prosumer with a non-zero level of energy consumption. Similarly, the

Algorithm 1 Algorithm for calculating the total cost

```
Input: $h$, $\mathcal{N}$, $\lambda_{b_h}$, $\lambda_{s_h}$, energy usage profiles
Calculate $SDR_h$ according to (8)
Calculate $\lambda_{e_h}$ according to (13)
Calculate $\lambda_{L_h}$ according to (30)
for all $n \in \mathcal{N}$ do
    Calculate $\gamma^{QD}_{n_h}$, $\Gamma^{QD}_h$ according to (15), (16)
    Calculate $\Delta^{QD}_{n_h}$ according to (17)
    Calculate $\tau^{L}_{n_h}$ according to (31)
    if $SDR_h \geq 1$ then
        Calculate the initial cost $C^{B}_{n_h}$ according to (14)
        Calculate $\psi^{QD}_{n_h}$, $\xi^{QD}_{n_h}$ according to (21), (22)
        Calculate the total cost $C^{F}_{n_h}$ according to (32)
    else if $SDR_h < 1$ then
        Calculate $\omega^{MG}_{n_h}$, $\omega^{UG}_{n_h}$ according to (52), (53)
        Calculate the initial cost $C^{B}_{n_h}$ according to (54)
        Calculate $\psi^{QD}_{n_h}$, $\xi^{QD}_{n_h}$ according to (56), (57)
        Calculate the total cost $C^{F}_{n_h}$ according to (58)
    end if
end for
```

Algorithm 2 Algorithm for calculating the total profit

```
Input: $h$, $\mathcal{N}$, $\lambda_{b_h}$, $\lambda_{s_h}$, energy usage profiles
Calculate $SDR_h$ according to (8)
Calculate $\lambda_{e_h}$ according to (13)
Calculate $\lambda_{L_h}$ according to (30)
for all $n \in \mathcal{N}$ do
    Calculate $\gamma^{QS}_{n_h}$, $\Gamma^{QS}_h$ according to (34), (35)
    Calculate $\Delta^{QS}_{n_h}$ according to (36)
    Calculate $\tau^{L}_{n_h}$ according to (31)
    if $SDR_h \leq 1$ then
        Calculate the initial profit $P^{B}_{n_h}$ according to (33)
        Calculate $\psi^{QS}_{n_h}$, $\xi^{QS}_{n_h}$ according to (40), (41)
        Calculate the total profit $P^{F}_{n_h}$ according to (42)
    else if $SDR_h > 1$ then
        Calculate $\mu^{MG}_{n_h}$, $\mu^{UG}_{n_h}$ according to (45), (46)
        Calculate the initial profit $P^{B}_{n_h}$ according to (47)
        Calculate $\psi^{QS}_{n_h}$, $\xi^{QS}_{n_h}$ according to (49), (50)
        Calculate the total profit $P^{F}_{n_h}$ according to (51)
    end if
end for
```

actual price at which a prosumer n sold energy to the microgrid in a time slot h can be determined by dividing the total profit ($P^F_{n_h}$) by the amount of energy sold ($QS_{R_{n_h}}$). Let $Pr^S_{n_h}$ denote the actual selling price of energy to the microgrid for a prosumer n in a time slot h, which is calculated as follows:

$$Pr^S_{n_h} = \frac{P^F_{n_h}}{QS_{R_{n_h}}}, \quad \text{where} \quad QS_{R_{n_h}} > 0 \tag{60}$$

In (60), the actual selling price can be calculated only for a prosumer with a non-zero level of energy production.

4. Results and discussion

This section presents the results of simulations to evaluate the proposed pricing model for a microgrid of prosumers. The microgrid consists of 100 prosumers ($N = 100$) that are capable of producing energy using photovoltaic systems.

To conduct the simulations, two real datasets are used. First, the energy consumption profiles for 100 prosumers are extracted from the first dataset [27] that contains energy consumption readings of London households between November 2011 and February 2014. Then, the energy production profiles for 100 prosumers are extracted from the second dataset [28] that contains energy data from domestic premises with high uptake of solar photovoltaic (PV) embedded generation between July 2013 and November 2014. Next, the energy consumption and production profiles of 100 prosumers are combined together to form the input data for the proposed pricing model. For a single-phase electricity connection, the voltage (V) is taken as 230 V. The amount of energy any prosumer exchanges with the MGO does not exceed 3.7 kW. The electrical wire resistance ρ is equal to 0.01 Ohm/m, whereas the distance d between any prosumer and the MGO is equal to 100 m. Since the energy usage forecasting mechanism is beyond the scope of this paper, predicted energy usage profiles are generated by adding noise to the real data.

Table 3
Green energy UK's TIDE tariff (weekday).

Time	Buying price (pence/kWh)
Midnight–7am	7.5p
7am–4pm	16.44p
4pm–8pm	32.55p
8pm–Midnight	16.44p

Table 4
Selling prices of energy for different suppliers.

Supplier	Selling price (pence/kWh)
Social energy	5.6p
Octopus energy	5.5p
E.ON	5.5p
Bulb	5.38p
SO energy	5p
OVO energy	4p
Scottish power	4p
EDF energy	3.5p
Shell energy	3.5p
SSE	3.5p
British gas	3.2p
Avro energy	3p
Utilita	3p
Utility warehouse	2p

To highlight the efficiency of the proposed pricing model, the simulations are conducted for two different tariffs:

- **TARIFF 1:** Based on [29], the buying price of energy from the utility grid (λ_{b_h}) in the UK is taken as 14.37 pence/kWh, whereas, the selling price of energy to the utility grid (λ_{s_h}) in the UK is taken as 5.24 pence/kWh [30]. In this case, the buying and selling prices of energy from (to) the utility grid do not vary during the day.
- **TARIFF 2:** The Green Energy UK's TIDE tariff [31] is used, where the buying price of energy from the utility grid (λ_{b_h}) varies during the day from 7.5 pence/kWh to 32.55 pence/kWh (Table 3). The selling price of energy to the utility grid (λ_{s_h}) is taken as an average (4.04 pence/kWh) of different selling prices of energy based on the data from different suppliers [32] (Table 4). In this case, the selling price of energy to the utility grid does not vary during the day.

To evaluate the proposed pricing model and emphasize its effectiveness in the total energy cost reduction is independent of the buying and selling prices of energy to (from) the utility grid, simulations are conducted for two different tariffs (**TARIFF 1**, **TARIFF 2**). For each tariff, the simulation results are compared with the baseline scenario when prosumers interact with the utility grid only (baseline), an approach in [22], and when prosumers interact with the microgrid using the proposed method. The simulations are conducted using PHP language on the machine with Intel Core i5 CPU @ 1.30 GHz and 4.00 GB RAM.

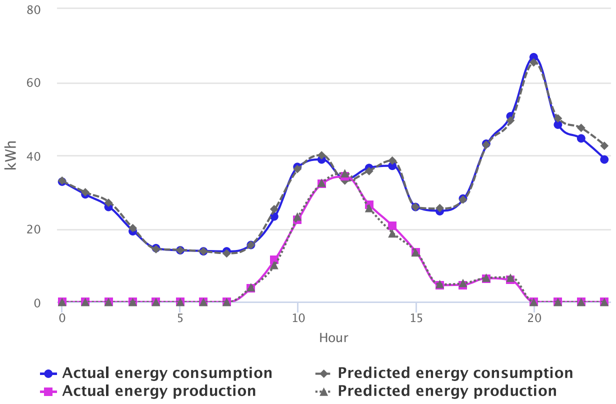

Fig. 4. Total predicted and actual energy consumption and production in the microgrid.

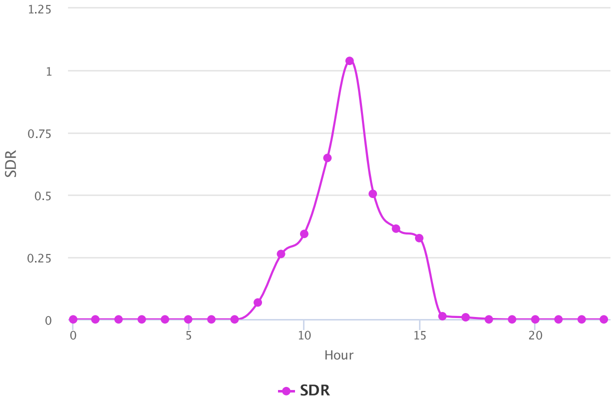

Fig. 5. Supply and demand ratio.

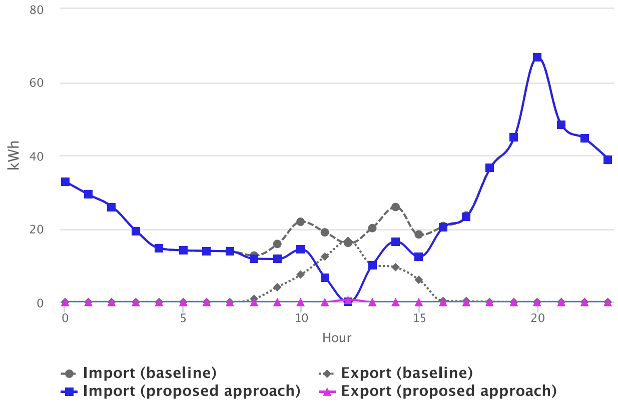

Fig. 6. Total amount of energy imported and exported from (to) the utility grid for the baseline scenario and using the proposed approach.

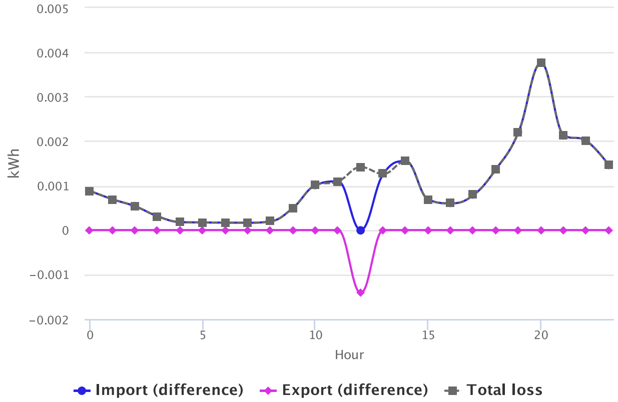

Fig. 7. Total energy transfer loss and the difference between the amount of energy imported and exported from (to) the utility grid using the proposed approach and an approach in [22].

It takes around 0.05 s on average to calculate the total energy usage cost and profit for 100 prosumers.

Fig. 4 shows the total actual and predicted energy consumption and production of all prosumers in the microgrid for one day. The increase in energy consumption can be observed during peak periods, namely from 8 a.m. to 3 p.m. and from 5 p.m. to 10 p.m. It can be observed that prosumers deviate from the predicted energy consumption profiles. For example, the total actual energy consumption is greater than the total predicted energy consumption in a time slot $h = 12$, whereas, in a time slot $h = 14$, the total predicted energy consumption is greater than the total actual energy consumption. The increase in energy production using photovoltaic systems can be observed from 8 a.m. to 4 p.m. It can be seen that prosumers deviate from the predicted energy production profiles. For example, the total predicted energy production is greater than the total actual energy production in a time slot $h = 12$, whereas the total actual energy production is greater than the total predicted energy production in a time slot $h = 14$.

Fig. 5 shows the supply and demand ratio (SDR_h) that depends on the total excess energy (QS_h^T) and the total shortage of energy (QD_h^T) in the microgrid. It can be seen that with the increase in energy production in the microgrid from 8 a.m. to 4 p.m., SDR also increases and reaches its peak in a time slot $h = 12$ ($SDR_{12} = 1.039$). It should be noted that in a time slot $h = 12$, excess energy (except the amount of energy that is needed to cover the losses) is sold to the utility grid, which also can be observed in Fig. 6 in a time slot $h = 12$.

By utilizing energy produced in the microgrid more efficiently, the demand for electricity from the utility grid can be reduced. Fig. 6 shows the total amount of energy imported and exported from (to) the utility grid for the baseline scenario and using the proposed approach. Due to the increase in energy production in the microgrid from 8 a.m. to 4 p.m. (Fig. 4), it can be observed that the amount of energy exported to the utility grid decreases during this time interval because of utilizing produced energy in the microgrid. In addition, when $SDR_h > 1$ ($h = 12$), the only small part of produced energy in the microgrid is sold to the utility grid (taking into account the losses). Thus, Fig. 6 emphasizes that the application of the proposed pricing model may reduce the amount of energy imported and exported from (to) the utility grid by utilizing energy produced in the microgrid more efficiently.

Fig. 7 shows the total energy transfer loss in the microgrid. It can be observed that the total loss reaches its peak in a time slot $h = 20$ because of the high demand for energy (high amount of energy exchanged with the MGO). It can be seen that there is no difference in energy imported from the utility grid in a time slot $h = 12$ because the excess is sold (exported) to the utility grid. On the other hand, there is a slight difference in energy imported from the utility grid from midnight to 11 a.m. and from 1 p.m. to midnight because the proposed approach takes into account the energy transfer loss, whereas the approach in [22] does not. In addition, there is no difference in energy exported to the utility grid because $SDR_h < 1$ from midnight to 11 a.m. and from 1 p.m. to midnight. The amount of energy exported to the utility grid using the proposed approach is less by 0.0014 kW compared with the approach in [22] because of the energy transfer losses.

Fig. 8 shows the total energy usage cost of all prosumers (**TARIFF 1**) in the microgrid for the baseline scenario, an approach in [22], and the proposed approach. It can be observed that with the increase in the energy production in the microgrid from 8 a.m. to 4 p.m., the total energy usage cost decreases because prosumers buy energy from the

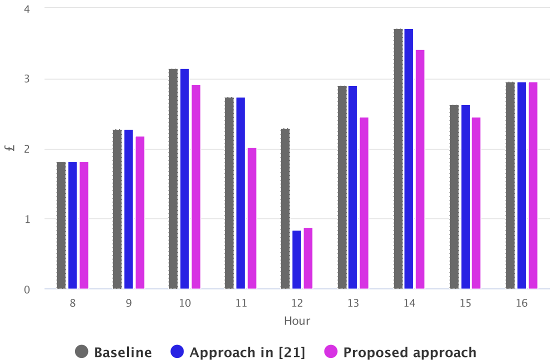

Fig. 8. Total energy usage cost of all prosumers (**TARIFF 1**) for the baseline scenario, an approach in [22], and the proposed approach from 8 a.m. to 4 p.m.

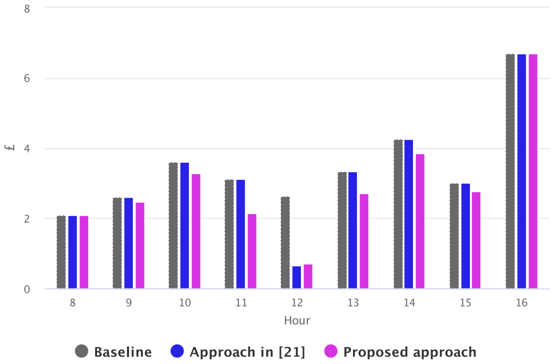

Fig. 9. Total energy usage cost of all prosumers (**TARIFF 2**) for the baseline scenario, an approach in [22], and the proposed approach from 8 a.m. to 4 p.m.

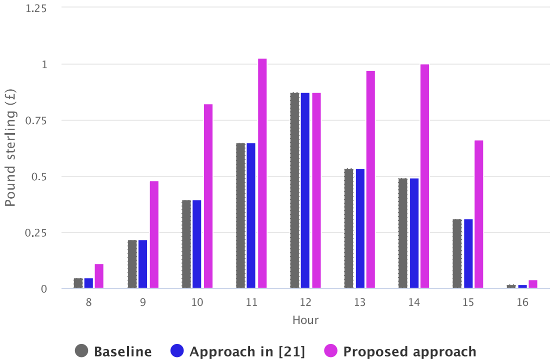

Fig. 10. Total profit of all prosumers (**TARIFF 1**) for the baseline scenario, an approach in [22], and the proposed approach from 8 a.m. to 4 p.m.

microgrid at a lower price (λ_{e_h}) compared with the buying price of energy from the utility grid (λ_{b_h}). In addition, it can be seen that using the proposed approach, the total energy usage cost of all prosumers is less in most time slots compared with the baseline scenario and the approach in [22]. In a time slot $h = 12$, the total energy usage cost is greater compared with the approach in [22] because of the energy transfer losses. The same pattern can be observed for the second tariff (**TARIFF 2**) in Fig. 9.

Fig. 10 shows the total profit of all prosumers in the microgrid for the baseline scenario, an approach in [22], and the proposed approach. Prosumers sell energy to the microgrid at a higher price (λ_{e_h}) compared with the selling price of energy to the utility grid (λ_{s_h}). Thus, the total profit of all prosumers when interacting with the microgrid using the proposed approach is greater compared with the baseline scenario and the approach in [22]. However, the total profit of all prosumers interacting with the microgrid is the same as the baseline scenario and the approach in [22] in a time slot $h = 12$ ($SDR_{12} = 1.039$) to make prosumers continue to participate in the microgrid. The same dynamics can be observed for the second tariff (**TARIFF 2**) in Fig. 11.

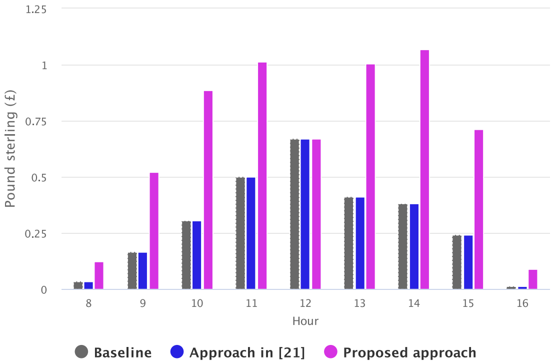

Fig. 11. Total profit of all prosumers (**TARIFF 2**) for the baseline scenario, an approach in [22], and the proposed approach from 8 a.m. to 4 p.m.

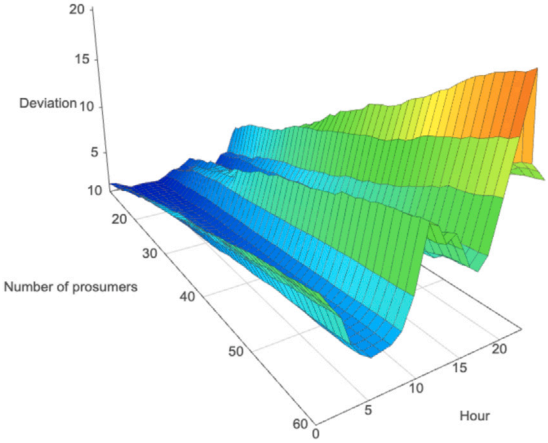

Fig. 12. Dependency of the total absolute deviation from the total predicted energy consumption on a number of prosumers in the microgrid.

Fig. 12 shows the dependency of the total absolute deviation from the total predicted energy consumption on the number of prosumers in the microgrid. It can be seen that with the increasing number of prosumers in the microgrid, the total absolute deviation also increases and reaches its peak (20.3182 kW) in a time slot $h = 20$ when there are 60 prosumers in the microgrid, whereas the minimum absolute deviation (0.5077 kW) can be observed in a time slot $h = 3$ for the microgrid that consists of 10 prosumers. Thus, the more prosumers in the microgrid, the more the total absolute deviation from the predicted energy consumption.

Fig. 13 shows the dependency of the total absolute deviation from the total predicted energy consumption on the number of prosumers in the microgrid in a time slot $h = 11$. It can be seen that with the increasing number of prosumers, the total absolute deviation also increases.

Fig. 15 shows the dependency of the randomly chosen prosumer's contribution to the total absolute deviation from the total predicted energy consumption on the total absolute deviation from the total predicted energy consumption. It can be observed that the contribution not only depends on the prosumer's absolute deviation from its predicted energy consumption (Fig. 14) but also depends on the contribution (deviation) of other prosumers. With the increasing total absolute deviation , the prosumer's contribution to the total absolute

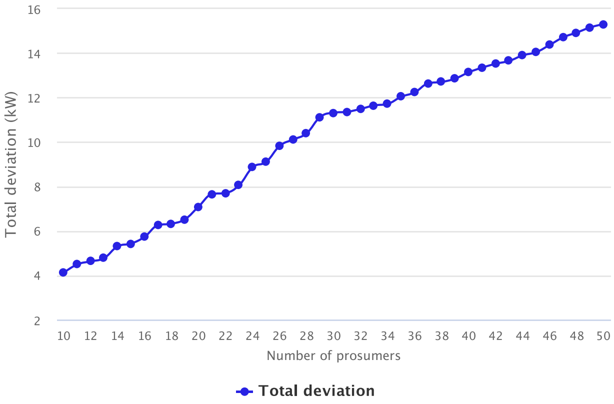

Fig. 13. Dependency of the total absolute deviation from the total predicted energy consumption on the number of prosumers in the microgrid in a time slot $h = 11$.

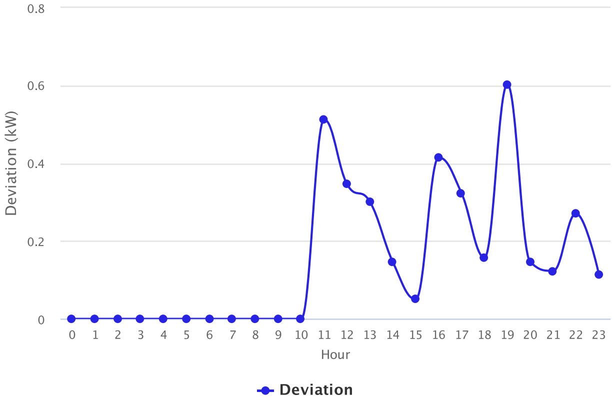

Fig. 14. Absolute deviation from the predicted energy consumption for a randomly chosen prosumer.

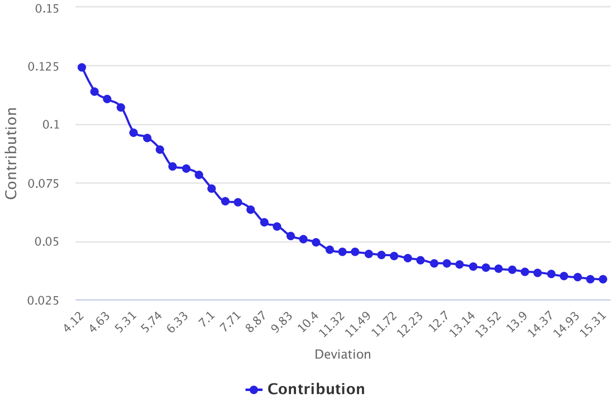

Fig. 15. Dependency of the randomly chosen prosumer's contribution to the total absolute deviation from the total predicted energy consumption.

deviation decreases because the prosumer's absolute deviation does not change with the increasing number of prosumers (total absolute deviation).

Fig. 16 shows the dependency of the energy usage cost for a randomly chosen prosumer on the total absolute deviation from the total predicted energy consumption in the microgrid in a time slot $h = 11$. It can be seen that with the increasing total absolute deviation , the energy usage cost for a prosumer decreases because the prosumer's contribution to the total absolute deviation decreases (Fig. 15), which affects the amount of penalty (22) that is added to the cost.

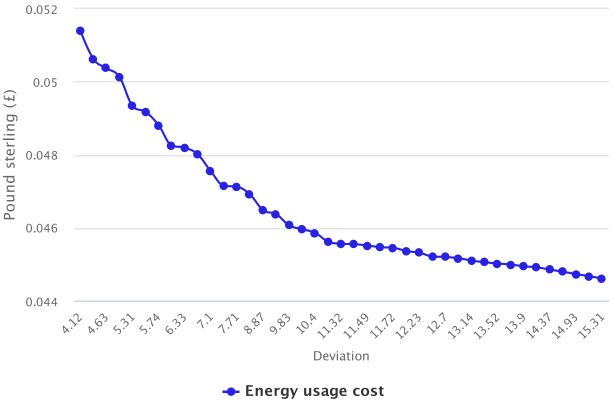

Fig. 16. Dependency of the total energy usage cost for a randomly chosen prosumer on the total absolute deviation from the predicted energy consumption in a time slot $h = 11$.

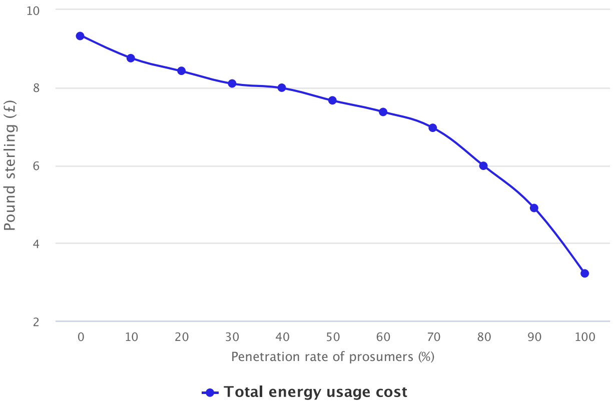

Fig. 17. Dependency of the total energy usage cost on the penetration rate of prosumers in the microgrid in a time slot $h = 12$.

Table 5
Decrease in the total energy usage cost of all prosumers (%).

Hour	TARIFF 1	TARIFF 2
8	0.38	0.35
9	5.3	4.96
10	10.61	8.76
11	55.33	31.19
12	61.41	73.37
13	36.41	18.64
14	14.11	9.67
15	9.82	7.7
16	0.02	0.02

The percentage decrease in the total energy usage cost of all prosumers (from 8 a.m. to 4 p.m.) is shown in Table 5. It can be seen that with the increase in the energy production in the microgrid (Fig. 4) from 8 a.m. to 4 p.m., the value of the decrease in the total energy usage cost grows. For the **TARIFF 1**, the maximum decrease in the cost is around 61.41% in a time slot $h = 12$, whereas for the **TARIFF 2**, the maximum decrease in the cost is around 73.37% in a time slot $h = 12$.

Fig. 17 shows the dependency of the total energy usage cost on the penetration rate of prosumers in the microgrid in a time slot $h = 12$. It can be observed that with the increasing number of prosumers (participants who can produce PV energy), the total energy usage cost in the microgrid decreases because more energy produced in the microgrid, which is sold and bought in the microgrid at a price λ_{e_h} instead of buying it from the utility grid at a price λ_{b_h}.

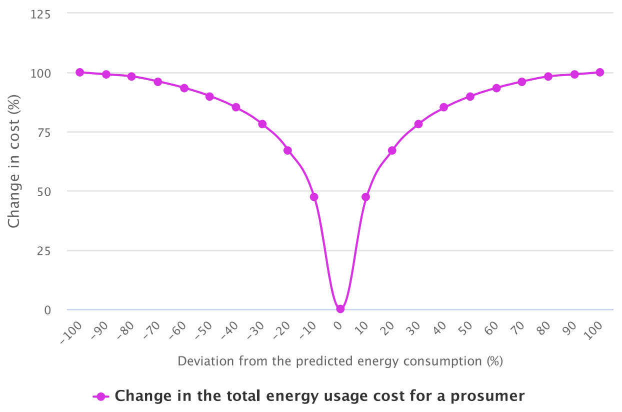

Fig. 18. Dependency of the total energy usage cost for a randomly chosen prosumer on its absolute deviation from the predicted energy consumption.

Fig. 19. Dependency of the total energy usage cost for all prosumers on the utility grid's buying and selling prices.

To assess the proposed pricing model, it is also compared with the existing works. The total energy usage cost of all prosumers in the microgrid with DR using the method proposed in [3] is equal to 88.13% of the energy usage cost in Peer-to-Gid (P2G) energy trading, which means that the decrease in the total energy usage cost is around 11.87%. The cost for each prosumer can be decreased maximum by 23.77% using the approach in [24]. The model in [33] can achieve the reduction in the cost of around 18.4% for low-demand customers only, whereas the approach in [34] achieves the decrease of around 11%. In contrast, the maximum reduction in the total energy usage cost of all prosumers using the proposed approach that was observed is around 73.37%. It should be noted that the proposed approach takes into account the energy transfer losses, which means that the energy usage cost for a prosumer includes the cost to cover the energy transfer loss.

5. Sensitivity analysis

This section presents the sensitivity analysis of the proposed pricing model. First, the dependency of the energy usage cost for a prosumer on the absolute deviation from its predicted energy consumption profile is analyzed. Secondly, the dependency of the total energy usage cost on the utility grid's buying and selling prices is assessed.

Fig. 18 shows the dependency of the total energy usage cost for a randomly chosen prosumer on its absolute deviation from the predicted energy consumption. It can be seen that when the prosumer does not deviate from its predicted energy consumption profile ($\gamma^{QD}_{n_h} = 0$), there is no change in the total energy usage cost. In contrast, with the increasing absolute deviation from the predicted energy consumption, the absolute deviation grows that leads to the increased total energy usage cost for a prosumer, which can be observed when the actual energy consumption decreases ($\gamma^{QD}_{n_h}$ changes from −10% to −100%) or increases ($\gamma^{QD}_{n_h}$ changes from 10% to 100%). For example, a prosumer n was expected to consume 1 kW of energy in a time slot h, whereas its actual energy consumption is 1.1 kW ($\gamma^{QD}_{n_h} = +10\%$), which means that the total energy usage cost will be 50% higher compared to the scenario when a prosumer does not deviate from the predicted energy consumption. The same energy usage cost will be if a prosumer's actual consumption is 0.9 kW ($\gamma^{QD}_{n_h} = -10\%$). Similarly, if the difference between the predicted and actual energy consumption reaches the level of 30%, the total energy usage cost will be 75% higher. Thus, the more a prosumer deviates from its predicted energy consumption profile, the more the total energy usage cost for this prosumer.

Fig. 19 shows how the change in the utility grid's buying (λ_{b_h}) and selling (λ_{s_h}) prices affects the total energy usage cost for all prosumers in the microgrid. First, the blue curve shows how the total energy usage cost for all prosumers depends on the change in the utility grid's buying price of energy, while the selling price does not change. It can bee seen that when the buying price of energy decreases, the total energy usage cost decreases. For example, if the buying price decreases by 5%, the total energy usage cost decreases by around 1.7%. When the buying price increases, the total energy usage cost also increases. For example, if the buying price increases by 10%, the total energy usage cost increases by around 3%. Secondly, the pink curve shows how the total energy usage cost depends on the change in the utility grid's selling price, while the buying price does not change. It can be observed that when the selling price decreases, the total energy usage cost increases, whereas with the increase in the selling price, the total energy usage cost decreases. It can be observed that the change in the buying price affects the total energy usage cost more than the change in the selling price. It happens because in a scenario, when $SDR_h < 1$, the shortage is bought from the utility grid, which increases the total energy usage cost, whereas the change in the selling price mainly affects the profit from selling energy. Due to the fact that the excess energy may be sold to the utility grid only when $SDR_h > 1$, most of the time the energy is bought from the utility grid to cover a part of the microgrid's demand or to cover the losses. Thus, the change in the buying price has more influence on the total energy usage cost of all prosumers.

6. Conclusion

This paper proposes a novel dynamic pricing model for a microgrid of prosumers with photovoltaic systems. In the scenario, when there is not enough energy produced in the microgrid to cover the demand of all prosumers, the proportions that reflect the amount of energy each prosumer can buy from the microgrid and from the utility grid are determined. Similarly, when the total energy produced in the microgrid exceeds the demand, each prosumer can sell at least some part of produced energy to the microgrid, whereas the rest is sold to the utility grid. Moreover, an algorithm for calculating penalties based on the prosumer's contribution to the total absolute deviation from the predicted levels of total energy consumption and production is proposed. The proposed approach takes into account the energy transfer losses; thus, the energy usage cost includes the cost to cover the losses.

Results show that with the increase in the energy production in the microgrid, the amount of energy imported and exported from (to) the utility grid decreases because of the utilization of the energy produced in the microgrid instead of buying (selling) it from (to) the utility grid, whilst the total energy usage cost can be decreased. One of the possible directions for future work is to extend the proposed pricing model by considering the predicted energy usage profiles as not a value but as an interval that is formed by the minimum and maximum predicted levels of energy consumption and production. Thus, in case a prosumer deviates from the predicted energy usage profile, it will be penalized if the actual absolute deviation exceeds the possible predicted absolute deviation .

CRediT authorship contribution statement

Veniamin Boiarkin: Conceptualization, Methodology, Software, Validation, Investigation, Writing – original draft, Visualization. **Mutukrishnan Rajarajan:** Supervision, Writing – review & editing. **Jafar Al-Zaili:** Supervision, Writing – review & editing. **Waqar Asif:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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