Research Article

Optimal Solution of Peer-to-Peer and Peer-to-Grid Trading Strategy Sharing between Prosumers with Grid-Connected Photovoltaic/Wind Turbine/Battery Storage Systems

Meryeme Azaroual,1 Djeudjo Temene Hermann,1,2 Mohammed Ouassaid,1 Mohit Bajaj,3,4,5 Mohamed Maaroufi,1 Faisal Alsail,6 and Sager Alsulamy7

1Department of Electrical Engineering Mohammadia School of Engineers (EMI), Mohammed V University, Rabat, Morocco
2Electric and Electronic Systems Laboratory, Department of Physics, Université de Yaoundé I, Yaoundé, Cameroon
3Department of Electrical Engineering, Graphic Era (Deemed to be University), Dehradun 248002, India
4Graphic Era Hill University, Dehradun, 248002, India
5Applied Science Research Center, Applied Science Private University, Amman 11937, Jordan
6Department of Electrical Engineering, College of Engineering, King Saud University, Riyadh 11421, Saudi Arabia
7Energy & Climate Change Division, Sustainable Energy Research Group, Faculty of Engineering & Physical Sciences, University of Southampton, Southampton SO16 7QF, UK

Correspondence should be addressed to Djeudjo Temene Hermann; djeudjotemenehermann@gmail.com

Received 12 April 2023; Revised 22 May 2023; Accepted 25 May 2023; Published 19 June 2023

Academic Editor: Manish Kumar Singla

Copyright © 2023 Meryeme Azaroual et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

This paper presents an energy management peer-to-peer (P2P) and peer-to-grid (P2G) trading strategy for power sharing between prosumers with grid-connected photovoltaic/wind turbine/battery storage systems. The optimal results are obtained using the “Fmincon” solver due to its ability to solve large-scale optimization problems. Two prosumers sectors are considered in this study that is the residential and commercial. The results show that for the residential consumer side, the load is satisfied by the energy from the grid, its own renewable energy system (RES), and the energy from the commercial consumer side RES during the first off-peak period (00:00 AM to 05:00 AM). During the peak pricing period (17:00 PM to 22:00 PM), the load is satisfied by the residential consumer’s battery and the commercial consumer’s battery, and no energy is bought from the grid due to the high price. Furthermore, 37.69% and 39.40% cost savings for residential and commercial, respectively, and a reduction of the bill by $42.26/day and $42.97154/day, respectively, are recorded. Significant grid energy savings for the developed P2P/P2G trading for prosumers and maximum daily cost savings are achieved compared to existing cases such as P2G only and P2P only. Finally, the residential consumer can achieve a greenhouse gases (GHG) emissions reduction of 141.88 kgCO2-eq and 176.99 kgCO2-eq net savings, while the commercial consumer can achieve 122.34 kgCO2-eq GHG emissions mitigation and 196.53 kgCO2-eq net savings.

1. Introduction

The production and use of sustainable energy to address the rapid growth in global energy demand in general and the electricity access deficit, in particular, have become major concerns in most countries [1]. The recent worldwide increase in electricity costs and the already known greenhouse gas (GHG) emissions have led to an appreciable transition from nonrenewable energy sources to renewable energy sources [2–4]. Electricity alone plays an important role in GHG emissions, with about 40% the CO2 emissions [5]. These renewable energy sources are known to be environmentally friendly since the greenhouse gases (GHG) emitted when using them are relatively very low compared
to the GHG emitted from nonrenewable energy sources [6, 7]. However, electricity generation from renewable energy sources is faced with the problem of their intermittent or fluctuating nature since they all depend on weather conditions, thus the best way to exploit these sources is by merging them to create a hybrid renewable energy system (HRES).

The kingdom of Morocco is blessed with renewable energy resources especially solar energy and wind, and its deficiency in nonrenewable energy resources has enhanced the interest of the kingdom in HRES. The high rate of urbanization in Morocco has made the residential sector to be the main energy-consuming sector in the country leading to an in the number of small-scale producers of electricity from HRES [2, 8]. Therefore, managing the excess energy produced by these small-scale producers becomes a problem since there is no existing energy code that permits small producers to sell their excess energy to the grid [2]. One way of solving this problem is the use of prosumer energy systems like an energy storage system which can serve as an energy consumer and/or an energy producer. The main challenge with this solution is the increase in the initial cost of the HRES. In order to address this challenge, another approach can be implemented, that is setting up a platform where there can be the exchange of excess energy between the residential sector and commercial sector found within the same municipality [9]. This approach is mainly based on the idea that two load demands can never have the same daily load profile, and so, there is a possibility of mutual assistance in energy balancing between these two sectors in a P2P energy sharing [9, 10]. The P2P energy-sharing strategy is possible if the two sectors under consideration here are all in the same municipality [10, 11].

The P2P energy-sharing strategy is a very new concept which is still at the stage of feasibility studies in developing countries like South Africa but has been known as a major development in developed countries where it is already possible to have P2P energy-sharing platforms [6, 9]. Some of these platforms include LichtBlick Swamp Energy (Germany) [6, 9, 12]; Smart Watts (Germany) [13]; The SonnenCommunity (Germany) [14]; PeerEnergyCloud (Germany) [15] Pico project (United Kingdom) [16]; Yeloja and Mosaic (United States of America) [17]; Vandezbron (Netherlands) [15]. All these cited works are, however, focused on big hybrid energy systems, and the P2P energy sharing is achieved by the use of the grid network [6].

In the current decade, several research works on the prosumers’ P2P energy sharing are being conducted worldwide. Abdella and Shuaib, using a case study, showed that an optimal power flow between the generations and load demands is possible through the P2P energy trading strategy [18]. Abdalla et al. made a thorough survey of existing models of optimization, technologies of electric power distribution, difficulties, operating technologies, and control algorithms that can be applied in implementing P2P energy trading [19]. Liu et al. discussed on how the concept of P2P energy sharing can enhance an electricity trading platform between prosumers and consumers who are unable to satisfy their load demand with the electric power they produced [20].

Long et al. discussed an aggregated double-stage command for peer-to-peer energy exchange in PV/storage systems of residential microgrid and outcomes illustrated a 30% reduction in the operation cost compared to a situation where the prosumers sell their excess power to the grid [21]. Sharma et al. modeled and studied a P2P energy-sharing strategy for a standalone system which included three prosumers with two having photovoltaic systems and one equipped with a hydrogen system storage [22]. Kusakana modeled an optimal P2P energy exchange of prosumers connected grid, using South Africa as a case study and considering two sectors (residential and commercial) [9]. Results showed an achievement of total cost reduction in a day of 62.71% in summer and 68.99% in winter in the residential sector [9]; 81.31% in summer and 31.69% in winter in the commercial sector. Kusakana also proposed an optimal energy exchange between two prosumers connected to grid whose energy conversion systems consist of photovoltaic and wind working in a P2P power-sharing configuration in Durban, South Africa [6]. A breakeven point after 4.3 years at $13,500 and a “true” payback period of 8.76 years were obtained with a 20-year lifecycle projected saving of around $60,536.82 or 47.42% [6]. To investigate how DER ownership affects each trader’s advantage in the P2P market, the study [23] created a game-theory-based decentralized trading strategy. The findings show that (a) P2P trading generally benefits each participating agent in the market from an economic perspective, but economic loss may occur in communities with high penetration rates of PV; (b) P2P trading generally benefits each participating agent in the market from an economic perspective; and (c) P2P trading generally benefits each participating agent in the market from an economic perspective. The paper in [24] proposes a P2P energy trading model for microgrids with distributed photovoltaic (PV) generation and battery energy storage systems (BESSs). This model’s simulation framework is described, with the assumption that the local community consists of 30 homes. The framework includes detailed constraints that include the customer load profile, PV system, BESSs, market signals like feed-in tariffs, and retail pricing. First, a P2P energy trading market allows individual consumers to post orders (buying or selling orders) and trade data. In addition, the microgrid operator can set fair real-time buying and selling prices for peer-to-peer energy transactions and authenticate the orders based on how to achieve the lowest possible overall energy consumption in microgrids. Thirdly, the orders can be carried out and finished automatically at the calculated best price. In order to determine the appropriate sizes of distributed generating sources, including energy storage systems, the authors in [25] suggest a peer-to-peer energy trading system based on multiobjective game-theoretic optimization for a clustered microgrid. The chosen architecture consists of three distinct microgrids, each of which can be made up of a combination of solar cells, wind turbines, and batteries to satisfy the demands of the residential loads. Two different criteria, the annual profit and the probability of a power supply failure, are taken into account when formulating a multi-objective function, and the Nash equilibrium-based game theory technique is modeled for clustered microgrids using
a particle swarm optimization algorithm to obtain suitable player sizes and payoff values. The results of the multiobjective function are examined and contrasted for the peer-to-grid and peer-to-peer energy trading systems. The paper in [26] looks at a demand side management (DSM) system that is coordinated with P2P energy trading among the households. It takes into account the elements that have a big impact on cost optimization, like storage, renewable energy, and microgrid. It solves the discomfort users experienced as a result of job delays. The research makes three contributions. The study is the first optimal model that incorporates DSM and peer-to-peer energy trading. The suggested model’s solutions provide the ideal microgrid energy and price for P2P trade, which was not previously taken into account. Bokkisam et al. [27] suggest a TEF that uses auction theory, contains a system of agents and uses an auctioneer to assist a transactive energy market (TEM). Additionally, it contains a system of agents and uses an auctioneer to assist a transactive energy market (TEM). Additionally, it permits P2P energy trading among the residential buildings in the community microgrid for potential financial gain. There are three agents in this framework: the auctioneer, the participants, and utility. The day-ahead internal market-clearing price and quantity are determined by the auctioneer, a managerial agent modeled after the auction theory. The participants are independent, logical thinkers who use demand response (DR) management to try to keep their electricity costs as low as possible. The simulation’s findings show that there will be substantial financial gains for each market participant as well as increased community self-sufficiency, self-consumption, and less reliance on the utility grid.

From the above literature survey, it is observed that

(i) No researcher has worked on the P2P energy-sharing arrangement for the case of the Kingdom of Morocco

(ii) The few studies conducted for the case of Morocco considered only prosumer energy systems like battery and did not try to implement it for other prosumers like the residential sector and commercial sector

(iii) Most researchers are mainly concerned with the economic and technical aspects of the systems, and none of them worked on the environmental aspect, that is, CO₂ emission

(iv) Furthermore, most researchers worked on systems, having PV as the main electricity generator, very few considered PV and wind turbine [6], and those who even worked on such systems considered few components in the systems and of course few power flow parameters

(v) Most researchers develop models for P2P without taking into consideration P2G energy trading management

For the purpose of narrowing the aforementioned research gaps, the authors of this present article proposed to work on an energy management peer-to-peer trading strategy sharing among prosumers with photovoltaic/wind turbine/battery storage systems connected to the grid.

This is done as follows:

(i) Propose an optimal P2P and P2G solution to reduce the costs of energy of grid-connected prosumers using photovoltaic and wind turbine with energy storage systems in Morocco, considering two sectors (residential and commercial)

(ii) Perform an environmental analysis of the system notably in terms of the emission of CO₂

(iii) Consider a system with many components and many power flow parameters (20 parameters)

2. Methodology

2.1. P2P and P2G Energy-Sharing Descriptions. The basic system is made up of two generators of renewable energy sources (PV and WT). The two prosumers considered in this study, that is, the residential prosumer (RPR) and commercial prosumer (CPR), have a PV/WT/battery system all connected to the main grid. When the power generated by each of the prosumers system has satisfied each of the prosumers load demand, the excess energy is stored in the battery storage system of each prosumer.

When any of the prosumers’ system has a shortage in supplying its own prosumer, power may flow from one prosumer in case its own system generates more than enough power than its load demand and its battery storage system. If this power can still not satisfy the load demand, power flows from the main grid to satisfy the load demand. The power sharing among the two prosumers in the proposed P2P and P2G configuration is depicted in Figure 1. The surplus power generated by the system may be sent to the storage system for charging purposes or channeled to the CPR depending on the state of charge of the storage system and the applicable pricing period of the grid. There are two battery storage systems; battery 1 represents the battery storage system of the residential prosumer, and battery 2 represents the battery storage system of the commercial prosumer. The various power sharing, or control parameters, from Figure 1 may be defined as follows: RER: RE sources of residential; REC: RE sources of commercial; Lₖ: load of residential, Lₑ: load of commercial. Pₐ: power from RER to battery 1 of residential; Pₖ: power from battery 1 of residential to Lₖ; Pₑ: power from the grid to battery 1 of residential; Pₕ: power from the grid to Lₖ; Pₐ: power from REC to RER to Lₖ; Pₖ: power from RER to the grid; Pₑ: power from battery 1 of residential to grid; Pₕ: power from REC to battery 2 of commercial; Pₑ: power from battery 2 of commercial to Lₑ; Pₖ: power from the grid to battery 2 of commercial; Pₑ: power from the grid to Lₑ; Pₖ: power from REC to Lₑ; Pₑ: power from REC to the grid; Pₑ: power from the battery of commercial to grid; Pₑ: power from REC to charge the battery of residential; Pₑ: power from the battery of commercial to supply Lₖ; Pₑ: power from REC to supply Lₖ; Pₑ: power from RER to charge the battery of commercial; Pₑ: power from the battery of residential to supply Lₑ; Pₑ: power from RER to supply Lₑ.
As shown in Figure 2, prosumers can trade energy among themselves using the P2P energy trading arrangement. The peer-to-peer energy-sharing models define the prices at which prosumers will exchange power and how to calculate the consumers’ energy bills.

2.2. Component Description

2.2.1. PV System. The useful power generated from the PV system of each prosumer is given by [2, 28–30]

\[ P_{\text{pv, out}} = A \times G \times \eta_{\text{pv}} \times [1 - \alpha(T_a - 25)], \]  

(1)

where \( P_{\text{pv, out}} \) is the useful power of the solar PV system; \( G \)
represents the solar irradiance; \( A \) denotes the surface area occupied by the PV; \( \eta_{pv} \) is the percentage (%) of useful power generated from PV system, respectively; \( \alpha = 0.005^\circ \text{C}^{-1} \) is the temperature influencing factor; and \( T_a \) defines the ambient temperature (°C).

2.2.2. Wind Conversion System (WCS). The useful power generated by the WCS of each prosumer is given by [2, 31]

\[
P_{w,\text{out}}(t) = \begin{cases} 
0, & \nu \leq v_{ci}, \nu \geq v_{co}, \\
v^3 \left( \frac{P_r}{v_{ci}^3 - v_{ci}^3} \right) - P_r \left( \frac{v_r^3}{v_{ci}^3 - v_{ci}^3} \right), & v_{ci} < \nu < v_r, \\
P_r, & v_r < \nu < v_{co}.
\end{cases}
\]

(2)

\( \nu \) is the wind speed (m/s) at 1-hour interval, \( v_{ci} \) is the starting wind speed (m/s), \( v_r \) is the nominal wind speed (m/s), \( v_{co} \) is the maximum permissible wind speed (m/s), \( P_r \) is the nominal power of the WCS (kW), and \( \eta_w \) is the percentage (%) of useful power generated from WCS.

2.2.3. Battery Storage System (BSS). The state of charge (SOC) of the BSS is a parameter which helps to determine the quantity of energy the BSS has at a given instant, and it can be expressed as follows [32]:

During the charging process, we have

\[
\text{SoC}(t) = \text{SoC}(0) + \frac{\Delta t \times \eta_{\text{ch}}}{P_{\text{nom}}} \times P_{\text{ch}}(t).
\]

(3)

During the discharging process,

\[
\text{SoC}(t) = \text{SoC}(0) - \frac{\Delta t \times \eta_{\text{dch}}}{P_{\text{nom}}} \times P_{\text{dch}}(t),
\]

(4)

where \( P_{\text{ch}} \) represents the BSS charging power; \( P_{\text{dch}} \) represents the BSS discharged power; \( \eta_{\text{ch}} \) and \( \eta_{\text{dch}} \) are the BSS charging and discharging efficiency, respectively; and \( P_{\text{nom}} \) is the nominal power of the BSS.

2.2.4. Modeling Grid. The cost of purchasing power from the utility grid is computed as follows:

\[
C_{\text{grid}}(t) = \sum_{t=1}^{N} \rho(t) \times P_{\text{grid}}(t),
\]

(5)

where \( \rho \) is the electricity daily price ($/kW), \( P_{\text{grid}} \) is the power purchased from the national grid (kW), and \( N \) is the number of samples for each day.

Among the measures taken at the national level, aimed at improving energy efficiency, the national office has established a new time of use (ToU) price concerning domestic

<table>
<thead>
<tr>
<th>Period</th>
<th>Winter</th>
<th>Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>On peak</td>
<td>Off peak</td>
<td>On peak</td>
</tr>
<tr>
<td>Hours</td>
<td>17 h to 22 h</td>
<td>22 h to 17 h</td>
</tr>
<tr>
<td>Residential</td>
<td>( \rho(t) ) : price of the kWh ($)</td>
<td>0.224</td>
</tr>
<tr>
<td>Commercial</td>
<td>( \phi(t) ) : price of the kWh ($)</td>
<td>0.242</td>
</tr>
</tbody>
</table>

| Table 1: ToU prices of the residential and commercial prosumer. |
Figure 5: Flowchart of the developed strategy with P2P/P2G trading.

Algorithm 1: Fmincon interior-point algorithm.

Initialize $t_p, i = 0$
Tolerances: $t_{\text{min}}, t_{\text{max}}$
Counter for inner iteration: $i_{\text{int}} = 0$
Information about: $x_0, lb, ub, c, ceq$
Dimension: $n, m, p, q$

**Repeat**
1. Create the constraints;
2. Execute the MATLAB function:
   $[x, F, output] = \text{Fmincon}(\text{Objective function'},..., \text{Constraints'})$;
3. $i_{\text{int}} = i_{\text{int}} + \text{output.iterations}$;
4. Update on an approximation: $x_{i_{\text{int}}} \leftarrow x$;
5. Lagrange multipliers update;
6. Update $t$;
7. $i = i + 1$
**Until** stop criterium
low voltage (LV) customers (excluding prepayment) whose mean electricity consumption in a month exceeds 500 kWh. Aiming to reach the peak of the evening where the kilowatt-hour is most expensive, ToU tariffs shown in Table 1 consist of charging the energy consumption in two-hourly intervals at two different rates: an expensive 5 hours lasting rate for peak hours and a cheaper 19 hours lasting rate for the rest of the time in a day.

The prices for the sale of electrical energy [33] according to the hourly positions are presented in Table 1.

2.2.5. Load Profile. Figures 3 and 4 depict the load demand profiles of the residential and commercial prosumers for the selected case. The two profiles are dissimilar in terms of peak demand occurrence. This is the reason why we implemented a peer-to-peer energy exchange platform between prosumers in these two sectors.

2.3. Greenhouse Gas Emissions (GHG). In this work, the GHG emitted by the HRES the grid was taken into account.

To evaluate the GHG released from the PV (GHGPV) and from WCS (GHGWCS), the following equations can be used:

\[
\text{GHGPV} = \sum_{t=1}^{24} P_{\text{pv, out}}(t) \times \varepsilon_{\text{pv}} \times \text{GWP},
\]

\[
\text{GHGWCS} = \sum_{t=1}^{24} P_{\text{w}}(t) \times \varepsilon_{\text{wt}} \times \text{GWP},
\]

where the global warming potential (GWP), \(\varepsilon_{\text{pv}}\) and \(\varepsilon_{\text{wt}}\) are the PV and WCS emission coefficients whose values are, respectively, to 0.045 kgCO2-eq/kWh and 0.011 kgCO2-eq/kWh, [34, 35].

The grid GHG emission is expressed as follows:

\[
\text{GHG}_{\text{Grid}} = P_{\text{grid-load}} \times \text{GWP} \times \varepsilon_{\text{grid}}.
\]

In Morocco, the \(\varepsilon_{\text{grid}}\) is the electricity-specific factor, which is equivalent to 0.731211458 kgCO2-eq/kWh [2].

<table>
<thead>
<tr>
<th>Table 2: Simulation parameters of the microgrid (MG) system.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameters</td>
</tr>
<tr>
<td>-----------------------------</td>
</tr>
<tr>
<td>A</td>
</tr>
<tr>
<td>Maximum PV power</td>
</tr>
<tr>
<td>Number of PV panels</td>
</tr>
<tr>
<td>(\eta_{\text{PV}})</td>
</tr>
<tr>
<td>(\eta_{\text{WT}})</td>
</tr>
<tr>
<td>Cut-in velocity</td>
</tr>
<tr>
<td>Cut-out velocity</td>
</tr>
<tr>
<td>Rated speed</td>
</tr>
<tr>
<td>Maximum WT power</td>
</tr>
<tr>
<td>Number of WT</td>
</tr>
<tr>
<td>SoC_{min}</td>
</tr>
<tr>
<td>SoC_{max}</td>
</tr>
<tr>
<td>SoC_{0}</td>
</tr>
<tr>
<td>Battery capacity</td>
</tr>
<tr>
<td>Cost of battery</td>
</tr>
<tr>
<td>(N_{\text{cycle}})</td>
</tr>
<tr>
<td>(F_{\text{grid}})</td>
</tr>
<tr>
<td>em_{pv}</td>
</tr>
<tr>
<td>em_{wt}</td>
</tr>
</tbody>
</table>

The following formula is used to compute the system’s overall GHG emissions or “GHG\_total” [2]:

\[
\text{GHG}_{\text{total}} = \text{GHG}_{\text{PV}} + \text{GHG}_{\text{WCS}} + \text{GHG}_{\text{Grid}}.
\]

In this study, the net savings for the suggested method are determined by calculating the GHG emissions in two scenarios. Two scenarios: one in which the load is met solely by the utility grid (UG), which is regarded as the baseline scenario (Base\_GHG), and one in which RES has been implemented. Therefore, the net savings are expressed as follows:

\[
\text{GHG}_{\text{net-saving}} = \text{Baseline}_{\text{GHG}} - \text{GHG}_{\text{total}}.
\]
with

\[ \text{Baseline}_{\text{GHG}} = P_{\text{Load}} \times \text{GWP} \times F_{\text{grid}} \]  (11)

\[ F_1 = \min \sum_{t=1}^{N} \left[ \rho_{(t)} \left( P_{3(t)} + P_{4(t)} \right) + \varphi_{(t)} \left( P_{10(t)} + P_{11(t)} \right) \right] \Delta t, \]  (12)

where \( F_1 \) is the function that needs to be minimized and is linked to the total amount of grid power purchased; \( \rho_{(t)} \) is the cost of energy linked to the applied residential ToU; \( \varphi_{(t)} \) is the cost of energy of the applied commercial ToU; \( t \) is the selected \( t \)th sample interval where the optimization is taking place; \( N \) is the total number of sample intervals \((N = 24)\); and \( \Delta t \) is equal to 1 hour for each sampling interval.

Before exchanging energy with the other prosumer, each prosumer must maximize their own energy production, according to the second objective function \( F_2 \). Consideration is given to a straightforward pricing scheme for the prosumers’ internal energy sharing. Models for this include

\[ F_2 = \max \sum_{t=1}^{N} \left[ \left( P_{5(t)} + P_{12(t)} \right) \right] \Delta t \]

\[ + \min \sum_{t=1}^{N} \left[ \varphi_{(t)} \left( P_{17(t)} + P_{16(t)} \right) \right] \Delta t \]

\[ + \rho_{(t)} \left( P_{20(t)} + P_{19(t)} \right) \Delta t \]  (13)
3.2. Constraints

3.2.1. Power Balance Model of the System. When the total amount of renewable energy, batteries, and the grid at each sample time \( t \) is exactly sufficient to meet the load demand \( L_R \) or \( L_C \), the system’s power balance equation is correct. This may be stated in the following way:

\[
P_{\text{RE}(t)} + P_{\text{bat}(t)} + P_{\text{grid}(t)} = P_{\text{load}(t)}. \tag{14}
\]

3.2.2. Renewable Energy Constraints. The total amount of renewable energy output generated should not be exceeded by the power needed to feed the load, charge the battery, and export to the utility grid. This can be expressed as follows for residential (RC) and commercial consumers (CC):

\[
P_{1(t)} + P_{5(t)} + P_{6(t)} \leq P_{\text{RE}(t)}, \tag{15}
\]

\[
P_{8(t)} + P_{12(t)} + P_{13(t)} \leq P_{\text{REC}(t)}. \tag{16}
\]

Equations (17) and (18) prohibit the import and export of grid power simultaneously for RC and CC, respectively. This can be formulated mathematically as follows:

\[
(P_{3(t)} + P_{4(t)}) \times (P_{6(t)} + P_{7(t)}) = 0, \tag{17}
\]

\[
(P_{10(t)} + P_{11(t)}) \times (P_{13(t)} + P_{14(t)}) = 0. \tag{18}
\]

Moreover, it should be prohibited to charge and discharge the battery at the same time. For RC and CC, this constraint can be rewritten as follows:

\[
(P_{1(t)} + P_{3(t)}) \times (P_{2(t)} + P_{7(t)}) = 0. \tag{19}
\]
In the case of the developed P2P and P2G energy trading management model, the power exchanged between the RC and CC is not permitted at the same time. This can be, respectively, expressed as follows:

$$
\left( P_{8(t)} + P_{10(t)} \right) \times \left( P_{9(t)} + P_{14(t)} \right) = 0.
$$

(20)

In the case of the developed P2P and P2G energy trading management model, the power exchanged between the RC and CC is not permitted at the same time. This can be, respectively, expressed as follows:

$$
\left( P_{15(t)} + P_{16(t)} + P_{17(t)} \right) \times \left( P_{18(t)} + P_{19(t)} + P_{20(t)} \right) = 0.
$$

(21)

3.2.3. Battery Limitations. The SoC boundaries are stated in the following way:

\begin{align*}
SoC_{\text{min}} & \leq SoC(t) = SoC(0) + \frac{\Delta t \times \eta_{\text{dch}}}{P_{\text{nom}}} \times \left( P_{1(t)} + P_{3(t)} \right) \\
- \frac{\Delta t}{P_{\text{nom}} \times \eta_{\text{ch}}} \times \left( P_{2(t)} + P_{7(t)} \right) & \leq SoC_{\text{max}}.
\end{align*}

(22)

Residential prosumer:

\begin{align*}
SoC_{\text{min}} & \leq SoC(t) = SoC(0) + \frac{\Delta t \times \eta_{\text{dch}}}{P_{\text{nom}}} \times \left( P_{8(t)} + P_{10(t)} \right) \\
- \frac{\Delta t}{P_{\text{nom}} \times \eta_{\text{ch}}} \times \left( P_{9(t)} + P_{14(t)} \right) & \leq SoC_{\text{max}}.
\end{align*}

(23)

Commercial consumer:

3.2.4. Grid Power Limits. The limit of the grid power exchanged is subjected to the following constraints:

\begin{align*}
0 & \leq P_{\text{grid--import}(t)} \leq P_{\text{grid--import}}^{\text{max}}, \\
0 & \leq P_{\text{grid--export}(t)} \leq P_{\text{grid--export}}^{\text{max}},
\end{align*}

(24)

(25)

where $P_{\text{grid--import}}^{\text{max}}$ is the maximum amount of grid power that can be fed into the utility grid.
The energy management strategy under P2P trading is presented in Figure 5. Each prosumer’s renewable energy is first used to power its own load and BSS, and then any surplus RE is shared with the other prosumer to make up for its lack of load and BSS. Then, after addressing the load and storage needs of all prosumers, the remaining RE is exported into the utility grid. The excess RE and BSS of other building peer can be used to make up for the load shortage experienced by the prosumer after its own source of renewable energy and BSS has been exhausted. Finally, to make up for the microgrid’s unmet load deficiency, energy is imported from the utility grid.

3.3. Algorithm Formulation. Several “Fmincon” methods utilize this sort of input since the “Fmincon” solver uses the Hessian as an optional input in addition to the interior point and active set (Algorithm 1). The interior-point technique was selected for the “Fmincon” solver in this study because it can quickly converge and can address large-scale optimization issues [36].

The solver can be formulated as follows [37]:

$$\begin{align*}
\text{Min/Max } F(x), \text{ subject to } & \left\{ \begin{array}{l}
c(x) \leq 0, \\
c_\text{eq}(x) = 0, \\
Ax \leq b, \\
A_\text{eq}x = b_\text{eq}, \\
lb \leq x \leq ub.
\end{array} \right.
\end{align*}$$ (26)
Next, \( t_{\text{int}} \) and \( i \) define the inner and outer iteration counters, respectively; \( t_{\text{min}} \) and \( t_{\text{max}} \) are the regularization parameter and the external iterations boundaries, respectively; \( t_0 \) is the starting value of the regularization parameter.

3.4. Resource and Model Parameters. The sampling time is 60 minutes, and the control horizon is 24 hours. Figures 6 and 7 show, respectively, the hourly solar irradiance (SI) and wind speed for the chosen winter in Rabat city, Morocco. Table 2 is a list of the parameters.

4. Simulation Results and Discussion

The simulation is performed for a time horizon of 24 hours and a sampling time of 1 hour. The algorithms are executed on a computer with an Intel Core i7 processor and 8GB of RAM using MATLAB (R2015a).

4.1. Optimal Control for Residential Consumer Side. Figures 8–11 show the power flows from various sources providing the RC. Throughout the first off-peak period from 00:00 AM to 05:00 AM, the demand is low; therefore, the residential demand is supplied by the grid (P4) and supplemented by its own RES (P5) and BSS (P2). A small contribution from the CC’s battery (P16) is used to satisfy the RC’s demand. As the electricity price is low during this period, the battery is charged from UG (P3). An excess from BSS is sold to the grid (P7).

The second off-peak price period, lasting from 5:00 AM to 17:00 PM, the RC is supplied mainly by RES as the first priority (P5) and battery (P2) as a second resort. There is no power purchased from the grid during this period. Therefore, the needed power is shared by the battery (P16) and
RES (P17) of the CC to that of the RC. It can be seen from the figure that the BSS of RC is charged principally via RES (P1) and then the RES of CC (P15). Thus, a small power is used from the grid for storage (P3). An important surplus power generated by the RES and battery is sold to the UG (P6 and P7).

Throughout the peak pricing period from 17:00 PM to 22:00 PM, the load demand reaches its peak, and the intensity of solar and wind decreases; therefore, the RES cannot supply the demand. An important contribution from P15 is used in conjunction with the battery’s RC and those of CC to meet the residential load (P16 and P17). It can be seen in Figure 9 (P3) that the battery is charged from the grid for further use. There is a power sold to the UG (P6 and P7) to generate revenue.

4.2. Optimal Control for Commercial Consumer Side. Figures 12–15 show the power flows from various sources providing the CC. The CC is benefiting from using the renewable energy sources (RES) because its daily generation profile strongly matches the load profile for the majority of economic activity. For the first period lasting from 00:00 AM to 05:00 AM, the commercial demand is low, and it is supplied by grid (P11), WT (P12), and BSS (P9). Also, a small quantity of power from battery’s RC is used (P19). As the cost of energy is low during this period and no other sources are used to charge the battery, the power is purchased from the grid to store the energy (P10).

During the second price period from 05:00 AM to 17:00 PM, a significant contribution from the RES is used to supply load demand (P12). Then, the battery of CC is discharged to meet the required energy (P9) with a small contribution from the power grid (P11). This is due to the shared power from a battery and of RC (P19 and P20). As there is enough power from RES (P8) and from RES’s RC (P18), the battery is charged for further use. A small contribution from the grid is used to complete the shortage (P10). As can be seen in Figure 14, an important amount of revenue can be generated by selling the surplus power from batteries and RES (P13 and P14) to the UG.

Throughout the peak pricing period from 17:00 PM to 22:00 PM, the commercial demand is relatively high and reaches its peak; therefore, the CC is supplied by a battery (P9) in conjunction with the grid (P11) and RES (P12). To meet the required power, BSS (P19) and RES’s RC (P20) are used. Figures 13 and 15 show that the BSS is charged during the period using excess power from RES (P8), grid (P10), and RC’s RE system (P18).

In the previous periods, there is a surplus of power sold to the UG from RE and the battery of the CC (Figure 14). Figure 16 depicts the SOC’s fluctuation as a result of charging and discharging operations. Each use of the battery to supply demand or sell to the UG results in a decrease in SOC for both consumers. When a battery is charged from RES, the grid, or another source, its SOC rises. For example, from 05:00 AM to 10:00 AM, the battery is used; therefore, it is recharged by P1, P3, and P15. The battery’s power is used to meet residential and commercial demand, with any excess sold to the grid by P2, P7, and P16. Consequently, the corresponding SOC decreases. The same observation applies to SOC’s commercial application.

Additionally, another comparison is made on power imported from the grid to satisfy load demand in the case of the baseline and the optimal one with P2P/P2G trading (Figures 17 and 18). From these figures, it is obvious that
there is a significant decrease in power flow with the P2P/P2G arrangement in the residential and commercial prosumers.

4.3. Economic and Environmental Analysis

4.3.1. Economic Aspect. The baseline cost is the amount that the consumer is expected to pay in the absence of optimization, whereas the optimal cost is the cost of grid energy following the implementation of optimal control. According to the bill, grid energy was imported to power the load and battery storage system. The surplus of solar, wind, and battery energy sold to the utility grid is the source of income. Here is a calculation of the cost savings.

\[
\text{Cost.Saving} = \left( \frac{\text{Baseline Cost} - \text{Optimal Cost}}{\text{Baseline Cost}} \right) \times 100.
\]

(27)

The case study’s cost savings per day are shown in Figures 19 and 20, and the findings illustrate that the suggested model’s optimal control offers a sizable benefit. Each customer experienced a maximum cost saving, a reduction of the bill of $42.26/day and $42.97154/day for residential and commercial, respectively, and cost savings of 37.69% and 39.40%.

Table 3 compares the revenues earn from the HRES in P2P trading with and without considering the P2G sharing schemes. The incomes are seen as having significant decrease in power flow with the P2P/P2G arrangement in the residential and commercial prosumers.

4.3.2. Environmental Aspect. Figure 21 demonstrates that the suggested model in the P2P-P2G energy-sharing scheme offers the best outcomes from an environmental standpoint, with the least overall GHG emissions and the greatest net savings. The RC can reach a 141.88 kgCO2-eq GHG emissions reduction and a net savings of 176.99 kgCO2-eq, whereas the CC can accomplish a 122.34 kgCO2-eq GHG emissions mitigation and a net savings of 196.53 kgCO2-eq.

<table>
<thead>
<tr>
<th>Table 3: Comparison of HRES in P2P/P2G trading.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Consumer</td>
</tr>
<tr>
<td>Revenues ($/day)</td>
</tr>
<tr>
<td>Peer to peer [9, 10]</td>
</tr>
<tr>
<td>Peer to peer and peer to grid</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 4: Cost savings in P2P/P2G trading of prosumers.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
</tr>
<tr>
<td>Baseline ($/day)</td>
</tr>
<tr>
<td>Grid-saved energy or energy not delivered in P2P/P2G (kWh)</td>
</tr>
<tr>
<td>Peer to grid only [38–41] ($/day)</td>
</tr>
<tr>
<td>Peer to peer [9, 10] ($/day)</td>
</tr>
<tr>
<td>Developed peer to peer/peer to grid ($/day)</td>
</tr>
</tbody>
</table>

5. Conclusion

In this paper, a model for the optimal operation of grid-connected prosumers in a peer-to-peer energy-sharing system is put forth. The developed model decreased operational costs for both consumers by maximizing the use of power from RES, optimizing internal power sharing between the consumers, and minimizing the consumption of electrical supply under the ToU tariff.

Residential and commercial customers are the ones who were chosen. The battery, WT, and PV in the model are all grid-connected. Using MATLAB software, a simulation of smart energy management is carried out to show the efficacy of the established technique. The findings show that the P2P/P2G system enables prosumers to profit from their own energy production and significantly reduces costs when compared to using P2P trading without grid interaction.
Therefore, the following conclusions can be drawn from the results:

(i) A maximum cost saving is reached in RC and CC with 37.69% and 39.40%, respectively. Comparing the HRES revenue from P2P trade with and without taking P2G sharing schemes into account, the capacity to sell power to the UG is perceived to have greatly grown in the first case.

(ii) The proposed modeling approach is efficient due to its ability to minimize the environmental impact, with lower GHG emissions for both prosumers. The net savings are about 176.99 kgCO2-eq for RC and 196.53 kgCO2-eq for CC.

(iii) A significant grid energy savings for the developed P2P/P2G trading for prosumers and maximum daily cost savings are achieved compared to existing cases such as P2G only and P2P. The study’s focus is on the technical viability of such proposed systems with P2P abilities, not on optimal system sizing.

Consequently, future work will include:

(i) The system’s life-cycle cost including the replacement and initial costs, to determine the project’s viability.

(ii) The lack of assessment of the capacity market for renewable energy technologies.

(iii) The use of capacity based incentive for assessing the optimal dispatch of HRES.

Data Availability

Data are available on request.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors’ Contributions

Equal time and effort were put in by each of the authors. The authors confirm the final authorship for this manuscript. All the authors have equally contributed to this manuscript.

Acknowledgments

The authors extend their appreciation to the Deputyship for Research and Innovation, “Ministry of Education” in Saudi Arabia for funding this research (IFKUSUOR3-262-1).

References


