Multi-Objective Optimisation for Energy Scheduling in Smart Grids using Peer-to-Peer Trading

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***Abstract*—Efficient scheduling of the sources within a community is essential to reduce the electricity-related cost as well as the carbon emissions from the community. A novel energy management strategy for community grids is introduced in this research, leveraging peer-to-peer trading and the multi-objective optimisation of the cost and carbon emissions in scheduling the diverse energy sources and battery storage systems within the community. The grid, photovoltaic farms, Combined Heat and Power plants, and battery energy storage are considered in this paper, and our approach, underpinned by real-life data analysis, is used to find effective schedules for each source. The model is implemented on MATLAB and solved using the YALMIP optimisation toolbox to obtain optimal scheduling of the sources. An operation cost savings of up to 62.5% is achieved in a range of scenarios, highlighting the importance of optimal source scheduling in smart grids.**

***Index Terms*—Energy Management System, Multi-objective Optimisation, Pareto Optimisation, Smart grid**

Nomenclature

Δt Duration of time instance t.
η_{CHP} Efficiency of the CHP plant.
η_{ch} Charging efficiency of the BES.
η_{dis} Discharging efficiency of the BES.
C Total cost objective for the community (£)
$C_{\text{BES}}(t)$ Cost associated with BES at time t (£).
$C_{\text{BES}}(t)$ Cost associated with the BES at time t (£).
$C_{\text{CHP}}(t)$ Cost of electricity generation through the CHP plant at time t (£).
$C_{\text{GRID}}(t)$ Cost of electricity taken from the grid at time t (£).
$C_{\text{NG}}(t)$ Real-time price of natural gas at time t ($£/m^3$).
$C_{\text{op CHP}}(t)$ Additional operational cost due to maintenance of the CHP plant at time t (£/kWh).
$C_{\text{P2P}}(t)$ Cost associated with the P2P trading at time t (£).
$C_{\text{PV}}(t)$ Cost of electricity generation through PV at time t (£).
$C_{\text{p}}(t)$ Real-time grid price for energy purchase at time t (£/kWh).
$C_{\text{r BES}}(t)$ Additional operational cost for the BES at time t (£/h).
$C_{\text{s}}(t)$ Discounted P2P price for energy trading at time t (£/kWh).

This work was supported by the Engineering and Physical Sciences Research Council [grant numbers EP/X040518/1, EP/Y037421/1, EP/Y005376/1].

$E_{\text{BES min}}$, $E_{\text{BES max}}$ Minimum and maximum energy stored in BES (kWh).
$E_{\text{BES}}(t)$ Energy stored in the BES at time t (kWh).
FF Fill Factor.
k Charging flag indicator (1, if charging; 0, otherwise).
k_{I} Current temperature coefficient (A/^{0}C).
k_{V} Voltage temperature coefficient (V/^{0}C).
LHV_{NG} Lower heating value of natural gas (J/kg).
N_{solar} Total number of PV modules.
$P_{\text{CHP min}}, P_{\text{CHP max}}$ Minimum and maximum power output of the CHP plant (kW).
$P_{\text{CHP}}(t)$ Power output of the CHP plant at time t (kW).
$P_{\text{GRID max}}$ Maximum power purchased from the grid (kW).
$P_{\text{GRID}}(t)$ Power purchased from the grid at time t (kW).
$P_{\text{in max}}$ Maximum power input to BES (kW).
$P_{\text{in}}(t)$ Power input to the BES at time t (kW).
$P_{\text{load}}(t)$ Total load power at time t (kW).
$P_{\text{out max}}$ Maximum power output from BES (kW).
$P_{\text{out}}(t)$ Power output of the BES at time t (kW).
$P_{\text{P2P}}(t)$ Power traded peer-to-peer at time t (kW).
$P_{\text{PV min}}$, $P_{\text{PV max}}$ Minimum and maximum energy output from PV (kW).
$P_{\text{PV}}(t)$ Solar power output per hour (kWh).
R Carbon emissions from the CHP plant (g CO2).
$R_{\text{GRID}}(t)$ Carbon emissions from the grid at time t (g CO2e/kWh).
$R_{\text{u CHP}}$ Carbon emissions from the CHP plant per kWh of energy production (g CO2e/kWh).
$R_{\text{u GRID}}(t)$ Grid carbon intensity at time t (g CO2e/kWh).
$s(t)$ Solar irradiance at time t (W/m^2).
T Total time period under consideration.
t Specific time instance within the period T.
T_{A} Ambient temperature of PV module (^{0}C).
T_{OT} Nominal operating cell temperature of PV module (^{0}C).
$V_{\text{CHP}}(t)$ Volumetric consumption of natural gas for CHP at time t (m^3).
$V_{\text{MPP}}, I_{\text{MPP}}$ PV module voltage (V) and current (A) at maximum power point, respectively.
$V_{\text{OC}}, I_{\text{SC}}$ Open circuit voltage (V) and short circuit current (A) of a PV module.
w_1, w_2 Weighting factors for operational cost and carbon

emissions minimization objectives, respectively.

I. Introduction

IN the face of rising global energy demands, its associated carbon emissions, and the urgent need for sustainable practices, the role of efficient energy management systems has never been more critical. Nations such as the UK, Germany, and many others have signed pledges to reduce their respective carbon emissions to net zero by 2050 or sooner [1], [2]. This has led to a surge in research on ways to mitigate these emissions to enable the nations achieve their Net-Zero targets.

The power generation sector accounts for about 40% of the carbon emissions in the world in 2020 [3]; hence, a reduction in carbon emissions from this sector would lead to a substantial reduction in the world's carbon emissions. One prominent method in the mitigation of wasteful power generation is the implementation of smart grids [4]. This involves the utilisation of Energy Management Systems (EMS) to monitor and schedule the loads and sources in residential and industrial environments to drastically reduce the wasteful generation and usage of energy and enable more intelligent energy utilisation and scheduling [5]. This also opens up avenues for the bidirectional energy flow and can even reduce the arbitrage in the grid's carbon intensity and prices due to the intermittency of renewable sources in the grid [5]. The utilisation of smart grids can also lead to a reduction in grid carbon intensity, as seen in a study of the benefits of smart grid implementation in China [6].

Smart grids have to optimise between many different objectives and operational constraints set by the users and operators of the grid during their operation, such as carbon intensity reduction [6], cost reduction, stability constraints [7], renewable integration, and fault detection and resolution capabilities [8]. Some of these objectives can be contradictory to each other, such as in the renewable integration scenario where excess renewable power generation can reduce the reliability of the grid [7] and also lead to the overvoltage condition in some scenarios [9]. These scenarios require the use of multi-objective optimisation methods to balance the different objectives and select effective grid operation algorithms to allow optimal performance within the grid's operational constraints.

Extensive research has also taken place in the area of multi-objective optimisation and its utilisation in smart grids and EMS. It involves the use of algorithms to optimise two or more conflicting objectives. It encompasses methodologies that identify optimal solutions for complex problems. These solutions are found on the Pareto front, representing a set of non-dominated solutions in the objective space [10]. A non-dominated solution is one where no objective can be improved without worsening at least one other objective. A weighted utility function can be applied to select the most appropriate solution from this set, to reflect the decision-maker's preferences from the range of optimal solutions [11].

Peer-to-peer (P2P) trading is of significant importance in the future of energy networks and smart grids with multidirectional energy flow. P2P trading allows the trading of electricity between different users, typically during peak demand, and can help reduce the need for reserve generation capacity in the grid due to spikes in demand during peak times [12]. P2P trading has been shown to reduce the energy cost for prosumers in a wide range of scenarios while benefiting the grid through the reduction of peak demand [13] and reserve requirement [14].

Despite extensive research into the implementation of multi-objective optimisation within smart grids and P2P trading individually, there remains a lack of comprehensive studies that combine multi-objective optimisation of the user's objectives with the dynamics of P2P energy trading. Also, little has been done in the space of utilising the sources in the community to support the grid during times of higher grid carbon intensity. The grid carbon intensity is a measure of the amount of carbon emission per kWh of grid energy (gC02/kWh) and varies throughout the day, reflecting the carbon emissions of the sources employed in the generation of electricity [15]. This work introduces the joint consideration of the minimisation of the operational cost and carbon emission objectives in the smart grid of the community through the implementation of P2P trading. This is crucially important as smart grid technologies enable the bidirectional flow of energy from the wider grid network to the community-wide grid as well as between the prosumers in a community. Hence, it is essential to analyse the effective scheduling of the sources and energy storage in the community to optimally achieve its aims.

The main contributions from this work can be summarised as follows:

1) A Multi-objective optimisation of a community-wide EMS is proposed. The key objectives are operational cost minimisation and carbon emissions reduction in the community's grid.
2) P2P energy trading is jointly considered during the optimisation process. A simple and effective P2P energy pricing model is implemented in this work to address the grid overvoltage problem whilst allowing economical energy trading to take place.

II. System Modelling

The community-wide load considered in this paper consists of the aggregated hourly load in a residential setting. The primary energy source in this setting includes the grid, PV farm and the CHP plant in the community. The BES can also act as a source at appropriate times decided by the EMS. The community model can be seen in Fig. 1.

A. Solar Energy Sources

The solar energy source is utilised in this residential model. The available solar power is determined based on the irradiance in the area and the number of panels in the home [16], [17]. The power output from the PV per hour is derived using:

$$P_{\text{PV}}(t) = N_{\text{solar}} \times FF \times V(t) \times I(t),\ \forall t \in [1, T] \quad (1)$$

where

$$FF = (V_{\text{MPP}} I_{\text{MPP}})/(V_{\text{OC}} I_{\text{SC}}) \quad (2)$$

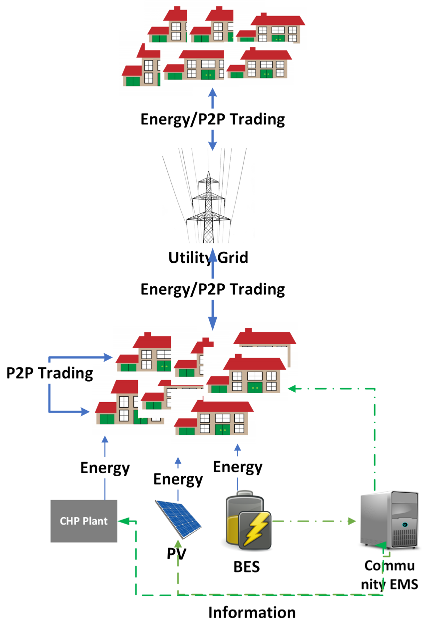


Fig. 1. Structure of Community Grid.

$$V(t) = V_{\mathrm{OC}} - k_{\mathrm{V}} T_{\mathrm{C}}(t) \tag{3}$$

$$I(t) = s(t)\left[I_{\mathrm{SC}} + k_{\mathrm{I}}\left(T_{\mathrm{C}}(t) - 25\right)\right] \tag{4}$$

$$T_{\mathrm{C}}(t) = T_{\mathrm{A}} + s(t)(T_{\mathrm{OT}} - 20)/0.8 \tag{5}$$

B. CHP Energy Source

The CHP plant, which consists of a microturbine, is used as a source of electricity and heat. The volumetric gas consumption is expressed as [18]:

$$V_{\mathrm{CHP}}(t) = (P_{\mathrm{CHP}}(t)\Delta t)/(\eta_{\mathrm{CHP}} LHV_{\mathrm{NG}}), \forall t \in [1, T] \tag{6}$$

The cost of running the CHP plant depends on the price of the feedstock, natural gas, and the operational cost of running the plant. It is calculated using

$$C_{\mathrm{CHP}}(t) = C_{\mathrm{NG}}(t) V_{\mathrm{CHP}}(t) + C_{\mathrm{op\ CHP}}(t) P_{\mathrm{CHP}}(t)\Delta t, \quad \forall t \in [1, T] \tag{7}$$

C. Battery Energy Source (BES)

The BES is used to store excess generation from the sources. The charging and discharging cycle of the battery is governed by the EMS to allow the maximisation of the user's goals. The energy stored in the BES, E_{BES} is modelled using [18]

$$E_{\mathrm{BES}}(t) = E_{\mathrm{BES}}(t-1) - (1-k) P_{\mathrm{out}}(t)\Delta t/\eta_{\mathrm{dis}} + k\eta_{\mathrm{ch}} P_{\mathrm{in}}(t)\Delta t, \ \forall t \in [1, T] \tag{8}$$

The cost of running the BES was calculated using the equation below

$$C_{\mathrm{BES}}(t) = C_{\mathrm{p}}(t) P_{\mathrm{in}}(t)\Delta t + C_{\mathrm{r\ BES}}(t)\Delta t, \forall t \in [1, T] \tag{9}$$

The charging and discharging cycle of the battery is managed by the EMS scheduling algorithm to meet the specific needs of the prosumers based on their requirement for cost or carbon emissions savings. The charging and discharging constraints and conditions are discussed in the constraints section.

III. Optimisation Problem Formulation

A. Objective Function

The objectives of the EMS involve reducing the cost of electricity usage for the community and the reduction of carbon emissions associated with energy use. These objectives are sometimes contradictory and warrant a multi-objective approach to meet the community's needs.

The EMS solves a combination of both objectives, which involves minimising the energy cost and carbon emissions due to the community's energy use. The combined objective can be written as:

$$F = w_1 C + w_2 R \tag{10}$$

The cost objective aims to reduce the cost of purchasing and utilising energy. This also includes the use of P2P energy trading and source scheduling to reduce the total cost of energy utilisation in the community. The different electricity sources have various generation costs, some of which are variable, such as the real-time price of electricity purchased from the grid, which is published on a day-ahead basis. It is, therefore, essential for the EMS to utilise this information for the optimal scheduling of different sources and P2P trading intervals for optimal source utilisation and cost minimisation. This is modelled using the following equations:

$$C = \sum_{t=1}^{T} \big(C_{\mathrm{CHP}}(t) + C_{\mathrm{PV}}(t) + C_{\mathrm{GRID}}(t) + C_{\mathrm{BES}}(t) - C_{\mathrm{P2P}}(t)\big) \tag{11}$$

where

$$C_{\mathrm{GRID}}(t) = C_{\mathrm{p}}(t) P_{\mathrm{GRID}}(t)\Delta t \tag{12}$$

$$C_{\mathrm{P2P}}(t) = C_{\mathrm{s}}(t) P_{\mathrm{P2P}}(t)\Delta t \tag{13}$$

The carbon emissions objective aims to reduce carbon emissions due to the utilisation of energy sources connected to the home, such as the grid, PV, and the BES. Each source has a different carbon intensity which depends on the feedstock used by the source in electricity production. Crucially, the carbon intensity of the grid fluctuates significantly interday and between days due to the intermittency of the renewable sources connected to the grid. The emission factors for the different sources, including the grid's carbon intensity, are found using the live tracker of the UK's carbon emission per source [15]. The carbon emissions for each day were calculated in the model using the following equation:

$$R = \sum_{t=1}^{T} \big(R_{\mathrm{GRID}}(t) + R_{\mathrm{CHP}}(t)\big) \tag{14}$$

where

$$R_{\mathrm{GRID}}(t) = R_{\mathrm{u\ GRID}}(t) P_{\mathrm{GRID}}(t)\Delta t \tag{15}$$

$$R_{\mathrm{CHP}}(t) = R_{\mathrm{u\ CHP}} P_{\mathrm{CHP}}(t)\Delta t \tag{16}$$

This objective can also enable the reduction of the grid's carbon emissions, as it would incentivise the utilisation of lower polluting sources and stored energy in the BES within the community during times of elevated grid carbon intensity. This, if adopted at scale, would also lead to a decrease in grid carbon intensity as the reduction in energy demand on the grid during times of higher grid carbon intensity enables lower utilisation of higher polluting sources within the grid.

B. Model Constraints

Specific constraints are placed in the optimisation algorithm to ensure a feasible solution to the EMS scheduling multi-objective problem is achieved. Some of the constraints added to the model can be seen below:

1) Power Balance Constraint:: The power balance constraint ensures that the energy supply always meets the demand at all points in time.

$$P_{\text{CHP}}(t) + P_{\text{PV}}(t) + P_{\text{GRID}}(t) + P_{\text{out}}(t) = P_{\text{load}}(t) + P_{\text{in}}(t), \ \forall t \in [1, T] \quad (17)$$

2) Power Output Constraints: The power output constraint ensures the schedule adopted by the EMS is feasible for all the sources in the community, and their minimum and maximum supply limits are not violated. The following constraints ensure the optimal operation of the EMS.

$$P_{\text{CHP min}} \leq P_{\text{CHP}}(t) \leq P_{\text{CHP max}}, \ \forall t \in [1, T] \quad (18)$$

$$P_{\text{PV min}} \leq P_{\text{PV}}(t) \leq P_{\text{PV max}}, \ \forall t \in [1, T] \quad (19)$$

$$P_{\text{GRID}}(t) \leq P_{\text{GRID max}}, \ \forall t \in [1, T] \quad (20)$$

3) BES Constraints: These constraints ensure the optimal operation of the BES and dictate the maximum operating parameters of the BES, such as the maximum discharge and charging rate. They also ensure that the battery is not being charged and discharged in the same interval, which can degrade the battery's lifetime.

$$P_{\text{in}}(t) P_{\text{out}}(t) = 0, \ \forall t \in [1, T] \quad (21)$$

$$0 \leq P_{\text{in}}(t) \leq P_{\text{in max}}, \ \forall t \in [1, T] \quad (22)$$

$$0 \leq P_{\text{out}}(t) \leq P_{\text{out max}}, \ \forall t \in [1, T] \quad (23)$$

$$E_{\text{BES min}} \leq E_{\text{BES}}(t) \leq E_{\text{BES max}}, \ \forall t \in [1, T] \quad (24)$$

IV. Energy Trading

Energy trading is implemented based on a P2P trading schedule and real-time pricing. To facilitate energy trading, a novel strategy involving a combination of source and energy trading optimisation is proposed. This ensures the EMS utilises complementary community energy management and energy trading strategies.

The strategy also involves sharing real-time network information between the prosumers in the grid and the Distribution System Operator (DSO). This is to prevent the overvoltage problem common during energy trading scenarios, especially during times of lower demand in the grid. The pricing strategy applies varying discounts to the real-time grid prices based on peak, intermediate, and off-peak times (see Table I). This discount to the real-time price can be viewed as the maximum energy trading price between the different parties participating during that time interval. The energy trading scenerio is summarized in Algorithm 1.

Algorithm 1 Enhanced Energy Trading Algorithm

```
Initialize system parameters and conditions.
Communicate with DSO for voltage and bus data.
Collect data of supply, demand, and grid conditions.
Set trading conditions based on goals and constraints.
Perform optimization to maximize objectives within regulatory and stability limits.
while conditions for energy trading are met do
    Check DSO data to ensure voltage is within limits.
    if DSO allows trading then
        Compute trade volume from E_BES, P_PV, and P_dem(t).
        Determine best trading action to meet objectives.
        Perform trade on the market.
    else
        Delay trading to maintain voltage and grid stability.
    end if
    Monitor system for changes in storage, demand, or grid.
    Adjust trading strategy based on new data.
end while
```

TABLE I
ELECTRICITY PRICING TIMEFRAMES AND DISCOUNTS

Timeframe	Discount Applied	Pricing Threshold
Peak	6%	85% - 100%
Intermediate	15%	70% - 85%
Off-peak	20%	0% - 70%

V. Results and Discussion

A. Input Data

This paper uses actual real-time pricing and the grid carbon intensity in the UK on different days as the simulation environment. The values of all the parameters used in the simulation can be seen in Table II.

The sources considered in this paper include the grid, PV farms, CHP plants, and the BES. The CHP plants, PV farms, and BES are managed within the community to provide energy to the community's residents. The effective scheduling of these sources is determined by the community's energy management system deployed in this paper to ensure the community's aims are achieved.

The loads considered in the model consist of the aggregated loads of 100 user profiles based on IEEE load data [19]. This ensures compatibility with a home energy management system model for individual residents in the community, in which the daily load profiles of the residents are shared with the community-level Energy Management System for effective scheduling of the sources within the community. This enables the community's EMS to focus on the optimisation of the sources and BES to achieve the objectives of the community. The electricity prices are based on the real-time price of electricity for a specific day in the UK. The real-time grid carbon intensity data is also utilised to minimise carbon emissions. The model is implemented in MATLAB, and the YALMIP toolbox [20] is used to simulate and optimise the scheduling of the sources.

TABLE II
PARAMETERS FOR SOLAR POWER, CHP, AND BES

Solar Power Parameters	
V_{MPP}: 31.0 V V_{OC}: 37.8 V N_{solar}: 250 units	I_{MPP}: 8.40 A I_{SC}: 8.95 A C_{PV}: 0.0096 £/kWh
CHP Parameters	
η_{CHP}: 0.85 C_{NG}: 0.0273 £/m^3 $P_{\text{GRID min}}$: 0 kW	C_{CHP}: 0.0017 £/kWh $R_{\text{u CHP}}$: 394 gCO_2/kWh
BES Parameters	
$\eta_{\text{ch}}, \eta_{\text{dis}}$: 0.9 $E_{\text{BES max}}$: 300 kWh $P_{\text{in min}}$: 0 kW	C_{BES}: 0.0014 £/kWh $E_{\text{BES min}}$: 0 kWh $P_{\text{in max}}$: 30 kW

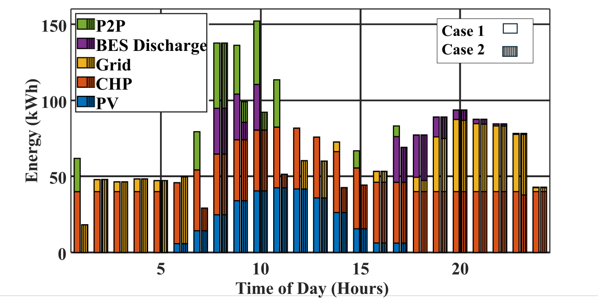
B. Optimisation Result Discussion

The optimisation is performed to identify effective scheduling cycles that maximise the objectives for the three scenarios considered:

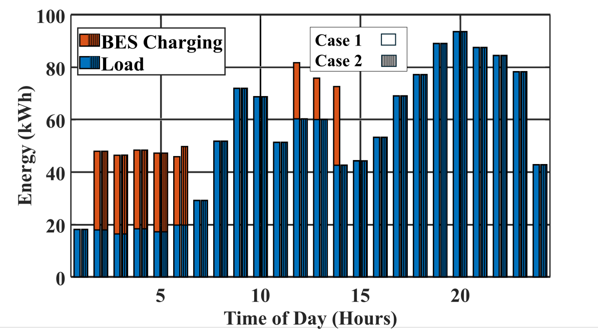
- Case 1 - Minimisation of community's carbon emission
- Case 2 - Combination of both objectives in a multi-objective problem

In Case 1, the focus is on the minimisation of operational costs. The BES is charged during times of lower real-time grid prices and higher PV energy generation, as seen in Figs. 2c and 2b, coinciding with periods of lower community loads and electricity prices. The energy storage facilitates the use of the stored energy during elevated grid real-time price periods and enables P2P trading at suitable intervals. Fig. 2a demonstrates the discharging cycle of the BES and the P2P trading schedule for the community. Discharging the BES during high grid price periods reduces grid utilisation, thus decreasing the community's energy costs. This allows for revenue generation from P2P trading of excess power stored in the BES, benefiting both the grid and the community by facilitating easier energy demand forecasting due to the peak shaving achieved using the BES. High CHP plant utilisation also occurs in this scenario, attributed to its lower operational cost per unit of energy compared to the grid. This approach is also beneficial for contingency planning. The lowest total cost is achieved here, with a total cost of £37.30 and carbon emission of $423.93\,\text{kg}\,CO_2$. This represents a 62.5% cost reduction and a 178% increase in carbon emissions compared to the grid-only baseline, due to the higher P2P trading and BES scheduling as seen in Fig. 3b.

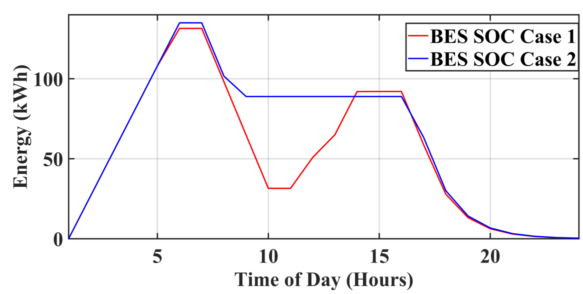
Case 2 adopts a multi-objective approach that combines cost and carbon emission minimisation. The BES charging and discharging schedule is depicted in Fig. 2c. The BES charges during periods of low grid prices and lower grid carbon intensity, enabling discharging during times of higher grid prices and carbon intensity as seen in Fig. 2b. Primarily, energy is sourced from the grid early in the morning, coinciding with low carbon intensity and grid prices, as shown in Fig. 2a. Notably, there is no power purchase during the interlude, even at lower grid prices, until the evening, when the higher load necessitates increased grid power purchases despite the higher carbon intensity. The energy purchased from the grid is lower



(a)



(b)



(c)

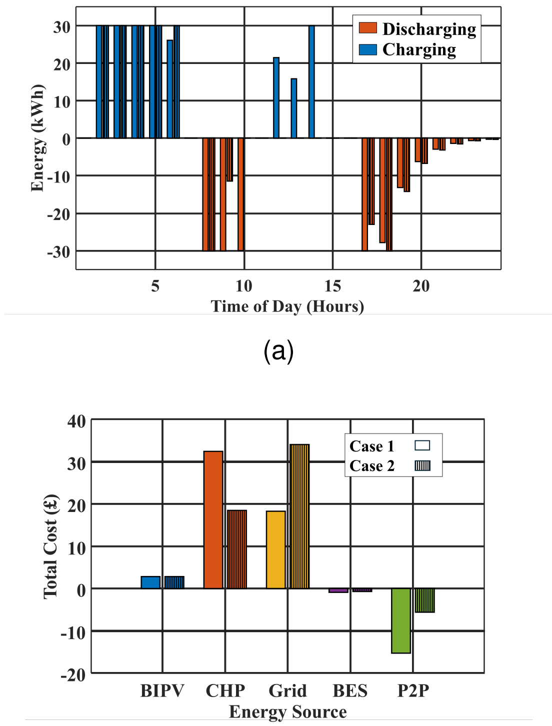
Fig. 2. Energy schedule of (a) sources; (b) load; and (c) BES.

due to the discharging of the BES during this period. The P2P trading schedule in this scenario is shorter than in Case 1 as the scheduling needs to satisfy both cost and emission reduction objectives, as seen in Fig. 2a. Economically, this scenario achieves an operational cost of £47.86, which is a 47.8% cost reduction compared to the grid-only implementation. However, the operational cost is 28% higher than that of Case 1. This significant cost increase is a result of the higher grid utilisation during periods of elevated grid prices, as seen in Fig. 3b. Carbon emissions of $289.06\,\text{kg}\,CO_2$, as shown in Table III, are 106% and 177% higher than the grid-only implementation and Case 1, respectively.

A Pareto front plot of the other solutions to the optimisation problem can be seen in Fig 4

VI. CONCLUSION

This paper presents a novel combination of multi-objective optimisation of operational cost and carbon emission, coupled



(a) (b)

Fig. 3. (a) BES charginng and discharging schedule; (b) Cost associated with sources.

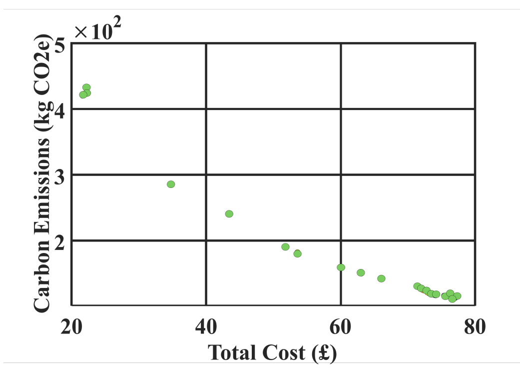


Fig. 4. Pareto Front of Optimisation Results

with P2P energy trading strategies in a community smart grid. A simple and effective P2P pricing strategy has also been implemented. Different sources, such as the grid, CHP plants, PV farms, and BES, have been integrated into the system alongside the aggregate load of the consumers in the community. The optimisation algorithm is implemented, and effective schedules for each source are found for two scenarios: cost minimisation and a multi-objective combination of cost and carbon emissions reduction. Both scenarios resulted in lower costs than purchasing from the grid, with up to 62.5% cost saving in the cost minimisation scenario. Careful selection of optimisation parameters is crucial to reflect community needs accurately. Future research could focus on integrating the home energy management systems of the consumers connected to the community's EMS.

TABLE III
COST AND CARBON EMISSIONS FOR DIFFERENT SCENARIOS

Scenario	Cost (£)	CO2 Emission (kg)
Case 1	37.30	423.93
Case 2	47.86	289.06
Grid-Only (No Intervention)	91.67	152.54

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