A Novel and Cost-efficient Energy Management System for Plug-In Electric Bus Charging Depot Owners

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Abstract: The integration of renewable Distributed Generations (DGs) has been a serious concern over reliable and satisfactory operation of the distribution system due to the intermittent nature of DGs. One of the solutions being proposed is the utilization of an Energy Storage System (ESS). However, without an appropriate energy management system, the integration of PV and ESS in a Plug-In Electric Bus Depot Charging (PEBDC) ecosystem can harmful to the LV feeder. Therefore, this paper proposed a cost-efficient energy management system that is based on a double-sided auction mechanism that provides a platform to perform energy trading among the selling and buying agents in the PEBDC ecosystem. A simulation has been performed for the energy management of the PEBDC ecosystem considering the middle months of all four seasons Summer, Autumn, Winter, and Spring corresponding to January, April, July, and October, respectively. A mixed-integer linear programming (MILP) model has been formulated for Bus Depot Owner (BDO) profit maximization and analysed using IBM ILOG studio with CPLEX solver.

Keywords: Plug-in Electric Bus; Plug-In Electric Bus Depot Charging; Bus Depot Operator; Energy Storage System; Low Voltage Feeder; Energy Management System.

Nomenclature

$E_{min}^{ESS}, E_{max}^{ESS}$	Lowest and highest ESS energy level at time interval ‘t’ in kWh
$P_{min}^{ESS}, P_{max}^{ESS}$	Lowest ESS and highest power limit at time interval ‘t’ in kW
$E_{min}^{PEB_{(i)}}(t), E_{max}^{PEB_{(i)}}(t)$	Lowest and highest energy level at time interval ‘t’ of PEB i in kWh
$C_{Sell}^{2G}(t), C_{Sell}^{2B}(t), C_{Sell}^{2PEB_{(i)}}(t)$	Selling price at time interval ‘t’ to grid, building and PEBs in $/kWh
$P^{PV2ESS}(t), P^{PV2B}(t)$	PV to ESS and building power flow at time interval ‘t’ in kW
$P^{PV2G}(t), P^{PV2C}(t)$	PV to grid and charger power flow at time interval ‘t’ in kW
$P^{G2B}(t), P^{ESS2B}(t)$	Grid and ESS to building power flow at time interval ‘t’ in kW
$P^{G2C}(t), P^{G2PEB_{(i)}}(t)$	Grid to charger and $PEB_{(i)}$ power flow at time interval ‘t’ in kW
$P^{PV2PEB_{(i)}}(t), P^{C2PEB_{(i)}}(t)$	PV and charger to $PEB_{(i)}$power flow at time interval ‘t’ in kW
$P^{ESS2G}(t), P^{ESS2C}(t)$	ESS to grid and charger power flow at time interval ‘t’ in kW
$P^{PV2ESS}(t), P^{PV2B}(t)$	PV to ESS and building power flow at time interval ‘t’ in kW
$P^{PV2G}(t), P^{PV2C}(t)$	PV to grid and charger power flow at time interval ‘t’ in kW
$P^{G2B}(t), P^{ESS2B}(t)$	Grid and ESS to building B power flow at time interval ‘t’ in kW
$E^{ESS}(t)$	Energy level of ESS at any time interval ‘t’ in kWh
$E^{PEB_{(i)}}(t)$	Energy level of $PEB_{(i)}$at time interval ‘t’ in kWh
$P^{PV}(t)$	PV power production at time interval ‘t’ in kW
$P_{max}^{PV}(t)$	PV power production limit at time interval ‘t’ in kW
$P^{G2ESS}(t)$	Grid to ESS power flow at time interval ‘t’ in kW
$C_{Pur}^{from\ G}(t)$	Purchasing price at time interval ‘t’ from the grid in $/kWh
$P_{max}^{Grid}(t)$	Highest power at time interval ‘t’ grid can deliver in kW
$x(t), y(t)$	ESS charging/discharging Binary variable

1 Introduction

The fast-growing participation of electric vehicles more specifically Plug-In Electric Buses (PEBs) and higher building energy consumption arising from increased urbanization will place a heavy burden on the power system [1]. The integration of renewable energy such as Photovoltaic (PV) system along with the Energy Storage System (ESS) into the Plug-In Electric Bus Depot Charging (PEBDC) ecosystem provides advantages such as i) surplus energy exported back to the grid to generate revenue for the depot owner, ii) PV panel has very low maintenance cost – it’s just needed to clean the panel couple of the times a year [2], and iii) provide 20-25 years warranty and have no wear and tear because there are no moving parts in the PV system [3]. However, the downsides are i) initial investment cost in the PV system is high, but the solar technology cost will go down due to the research and development in the PV technology [4, 5], ii) a larger area is required, therefore, places such as an airport, cricket stadium, or soccer field with a lot of solar panel spaces available on the rooftops and, iii) intermittency is the major problem of the PV system.

However, an effective integration and energy management of PV and ESS in the depot charging ecosystem can result in i) smoothing of the intermittency impact [6], ii) peak load reduction on the distribution grid [7], and iii) reduce the energy cost for the depot owner [8]. Considering the intermittent nature of solar PV, varying loads (PEB and building), and grid energy prices, an Energy Management System (EMS) is compulsory to monitor, control, and improve the economics of all the parties involved in the energy trading.

Therefore, this paper firstly presents an efficient EMS for the PEBDC ecosystem. Secondly, the EMS mathematical modelling consisting of PV, ESS, and chargers is developed. The different costs such as investment, operation, and maintenance and the constraints related to PV, ESS, charger, grid, and load are considered in the model are presented. Finally, in the results and discussion section, the energy trading among the parties involved in the PEBDC ecosystem for all four seasons i.e., Summer, Autumn, Winter, and Spring are presented.

The framework of the proposed study is shown in Figure 1. Firstly, i) the selling agent's data such as PV, ii) selling and buying agent (ESS and grid), and iii) and buying agents (load and PEBs) are provided as inputs into the IBM ILOG CPLEX optimization studio. Secondly, to perform the energy trading among the agents in the PEBDC ecosystem, an optimal EMS system (MILP based) is proposed which is subject to the optimal participation of the agents in the energy trading and guarantees the power flow between the selling and purchasing agents. The constraints such as i) total power generation and consumption, ii) ESS charging and discharging, iii) PEB battery safety, iv) PV generation, v) building load demand, and vi) power trading constraints are considered in the mathematical model. Lastly, the output in the form of PV and ESS power supply to building and PEBs are shown for all four seasons including i) Summer, ii) Autumn, iii) Winter, and iv) Spring.

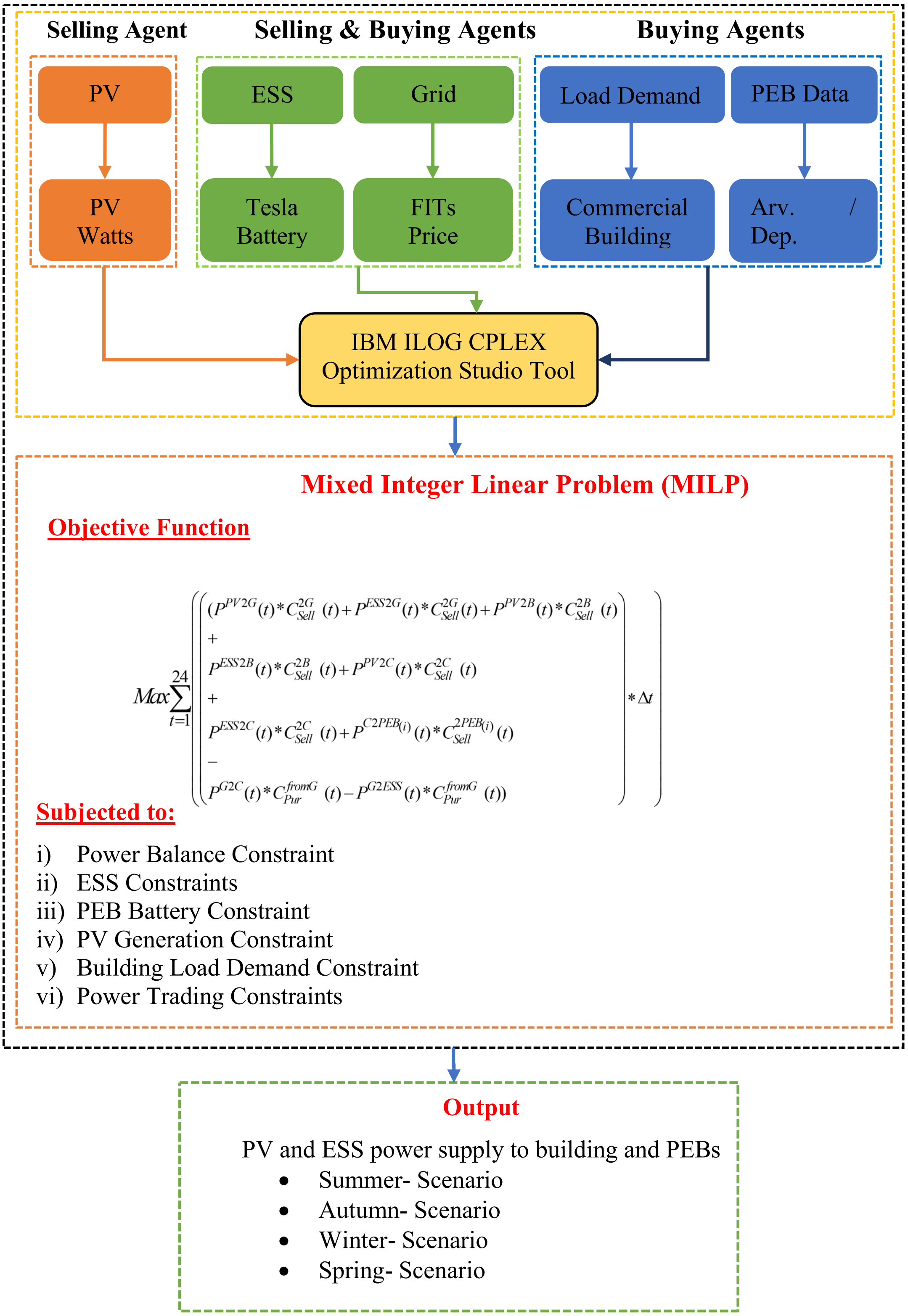

Figure 1 A Framework of the Proposed Study.

2 Proposed Energy Management System

The proposed EMS is based on the double side auction [9]. The double-sided auction is a process of selling and buying goods to multiple buying and selling agents. The potential buying and selling agents communicate their respective bids to the market institution and then the market institution chooses one price and clears the market [10]. In the PEBDC ecosystem scenario, ESS, PV, and grid act as a selling agent, while PEB, ESS, and grid act as a buying agent, and the aggregator act as a market institution. The buying and selling agents could participate in the energy market trading individually. However, the participation of individual agents at a system level is not feasible due to the following two reasons:

i) The power demand volume of individual buying agent may be lower than the required minimum volume to take part in the energy trading market, and

ii) The number of energy trading consumers/participants can be larger therefore the individual trade would be challenging to achieve.

Therefore, an aggregator is introduced to simplify the energy trading interaction between the selling and buying agents. A proposed EMS for the integration of PV, ESS, PEB, building, and grid in a PEBDC ecosystem is shown in Figure 2.

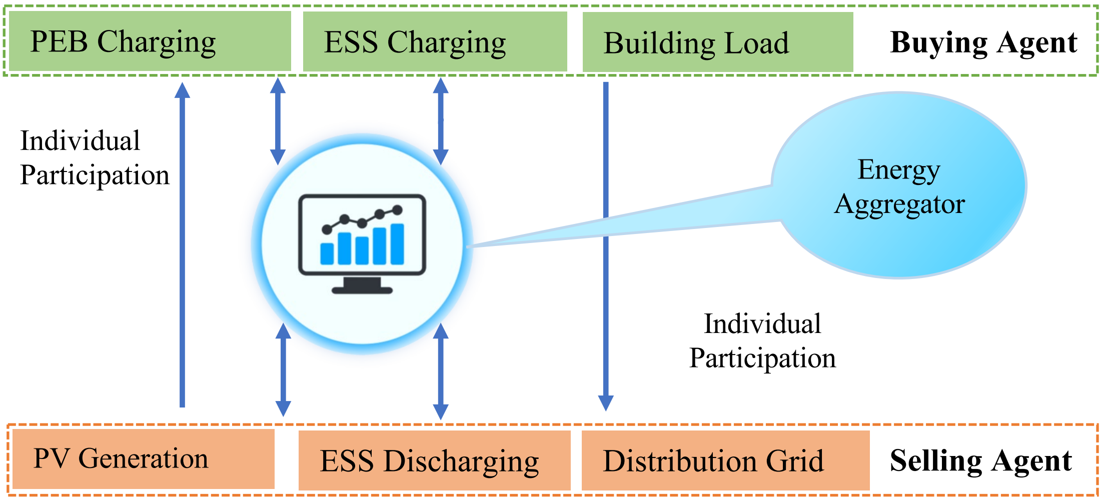

Figure 2 Components of the Proposed Energy Management System.

The proposed EMS implemented in the following three management steps:

i) In the primary management step, the energy aggregator in the EMS gathers information and sends instructions to each selling and purchasing agent.

ii) The secondary management step deals with the balancing of total available power from PV, ESS (discharging) and grid (as a source), and total load demand from PEBs, building, grid (as a load), and ESS (charging).

iii) The tertiary management step will minimize the economic structure of the PEBDC ecosystem by performing the optimal energy trading among the buying and selling agents.

3 Model Description

The PEBDC ecosystem consists of Bus Depot Owner (BDO) (that owns the PV, ESS, and chargers), PEBs, and access to the building (Auckland University of Technology campus buildings load (AC)) and the grid as shown in Figure 3. The role of energy aggregator (third part agent) in the EMS is to gather information and send instructions to each selling agent such as PV, ESS (discharge), grid and buying agents PEB, building, ESS (charging), and to the grid which is connected with a local micro source controller using a bidirectional communication system.

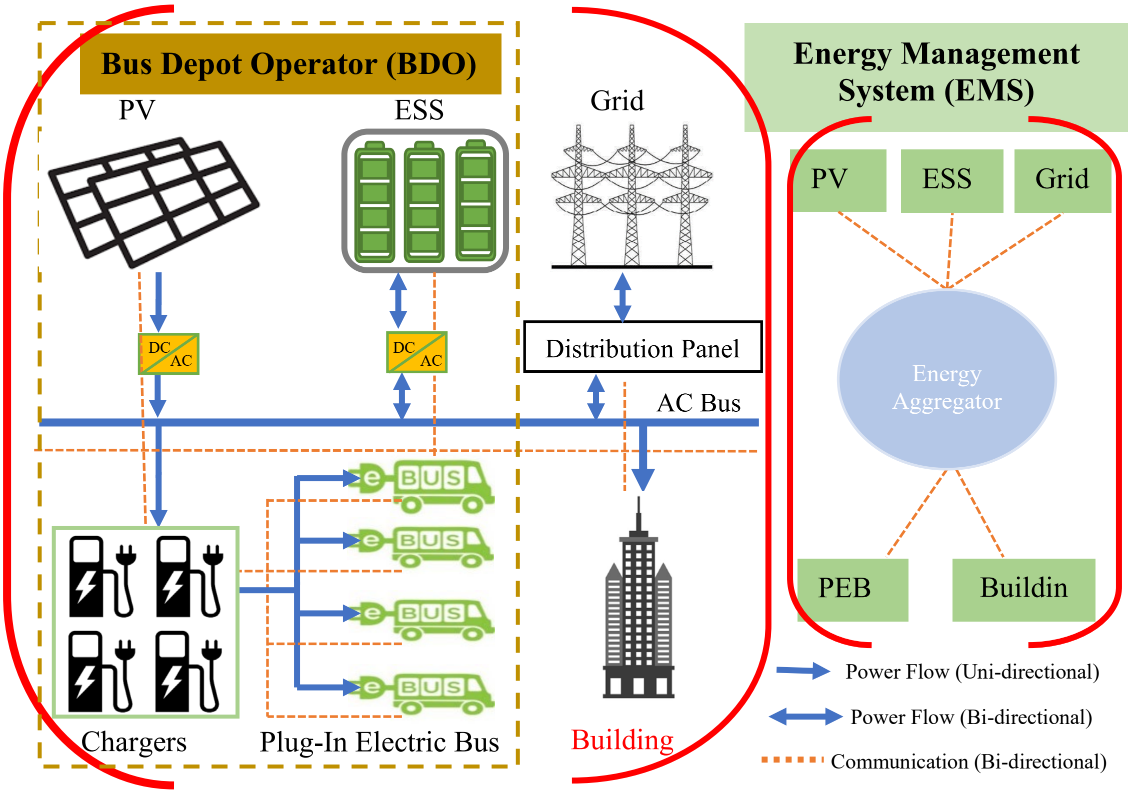

Figure 3 A Comprehensive Energy Management System for PEBDC Ecosystem.

The micro source controller coupled with the solar PV system will allow the flow of energy (surplus or deficit) to the AC bus or the grid through the distribution panel. The distribution panel will step up the voltage when the energy flows from PV and ESS to the grid and step down the voltage when the energy flows from the grid to the AC bus. The BDO will perform the energy trading among the agents in the PEBDC ecosystem while considering the Feed-in Tariffs (FITs) pricing scheme, PEB arrival/ departure schedule, building load, available energy due to PV generation ESS.

Figure 4 shows the flow chart of the proposed model which works on the double-sided auction-based algorithm. This algorithm provides a trading platform for the selling and buying agents which aim to search for the highest bidding agent from all the purchasing agents (PEB, building, ESS, and grid) in the bus depot and then performs the energy trading while buying the power from the grid during the low tariff or using the PV generation. The surplus power in ESS or PV production is feedback to the grid or building to fulfil the power demanded by the loads (building and grid).

From the flow chart (see Figure 4), firstly, the call for energy trading at any time interval *t* will check the balance of total available power between the selling agents (PV, and ESS (discharging)) and purchasing agent (PEB, building, and ESS (charging)). Then, in the case of surplus or deficit power, the EMS will take part in energy trading. Secondly, if the sum of PV power production and available power in the ESS is less than the demanded load (PEB and building) then the aggregator will purchase the power from the grid to fulfil the demanded power else the power is sold to the purchasing agent depending on the best bids offered by the agents. Finally, after the balanced condition is achieved, the EMS checks at *t+1* and repeats for every 10-minute interval.

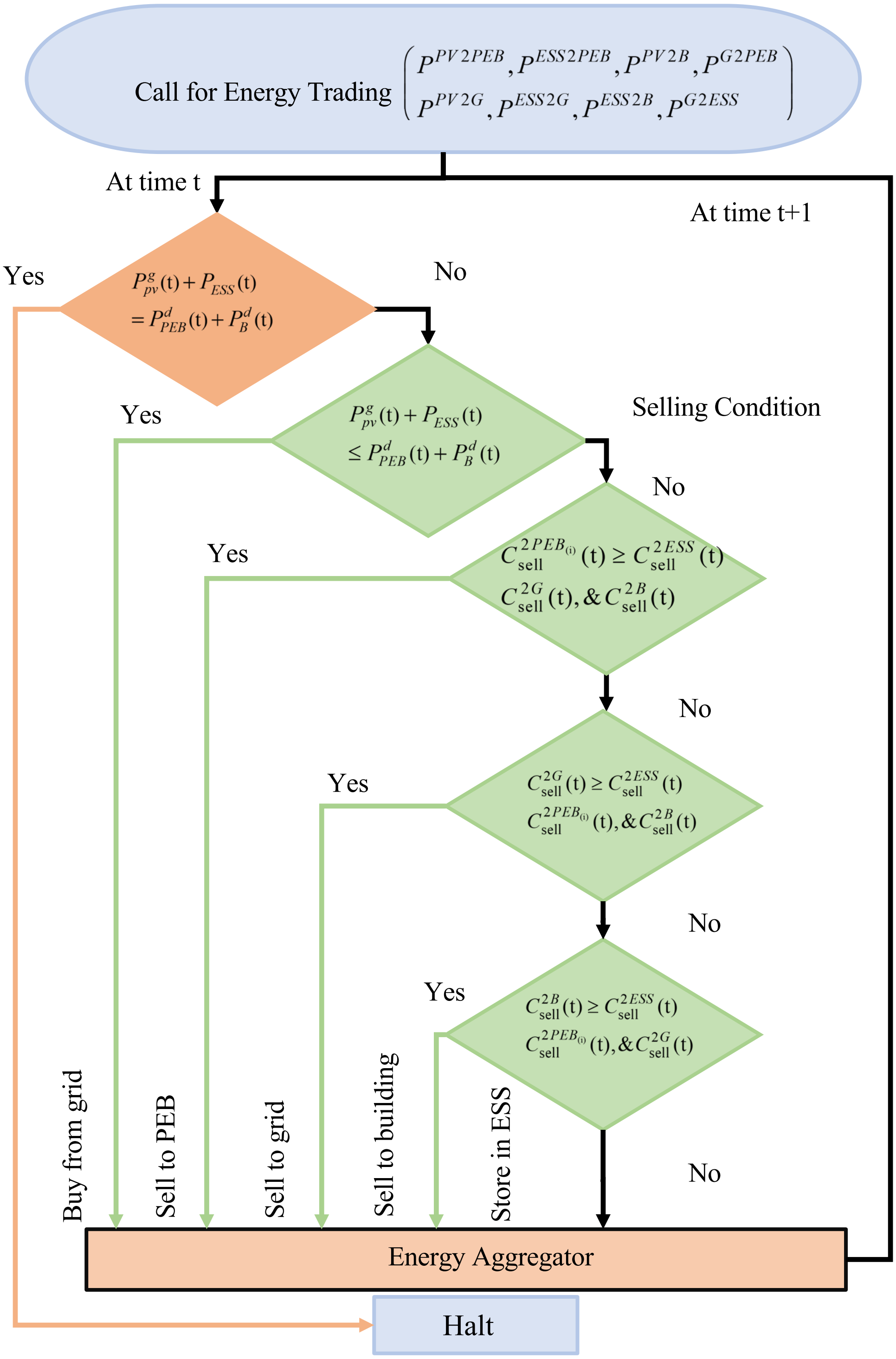

Figure 4. Flow Chart of the Proposed Energy Management Model.

5.1 Assumptions

i) The PEBDC ecosystem is placed at the Auckland airport consisting of: i) a 100 kW PV system is integrated with ii) 500kWh ESS, and iii) 12 chargers are available.

ii) Every single charger has two charging guns. Therefore, 12 chargers (for normal, off-peak, and peak time) are required to charge 44 PEBs (at different times) and this is the maximum charging capability of the BDO.

iii) To maximize the day-to-day BDO revenue, ESS purchases and stores power from the grid when its price is low. At other times, the power stored in ESS and that generated by the PV system may be exported back to the grid or sold to a building at 2/3 or 1/3 of the purchase cost from the grid [11] respectively, demonstrated in Figure.5.

iv) City of Auckland [12] solar profile irradiation, FITs prices from a distribution company Electra [13], and charger price from Idaho National Laboratory [14] are used as real-world data in the simulations.

v) PEB owner is decided to purchase the power from the BDO at a higher price than the actual price on the grid for the time intervals (1:00-7:00) am.

4 Mathematical Model

The purpose of the aggregator in the PEBDC Ecosystem is to purchase electric power from the main grid and/or use the generated power from the PV system and/or available power in the ESS to fulfil the power demanded by the purchasing agent such as a fleet of PEBs and/or a building. The aggregator generates profit by purchasing the electric power from the grid and storing it in the ESS while the grid price is low and sells it back to the grid when the grid offers a higher price. In this study, a mixed-integer linear programming (MILP) optimization model has been formulated to maximize the PEBDC Ecosystem profit by performing energy trading among the selling and purchasing agents. The system costs (capital investment, operation, and maintenance) of PEB chargers, ESS, and PV per day [15] presented in Table 1 are also considered during the simulation.

Table.1 PEBDC Ecosystem Components Costs (NZ$).

System Modules	PV	ESS	Charger
System Capacity	100 kW	500kWh	50 kW
Cost (W/Wh)	0.411	0.260	N/A
Projected life span (in year)	25	10	25
Aggregate System Cost	41,100	130,000	45,000
Recovery (cost/day)	3.67	4.986	2.99

5.1 Cost Model

The total cost of the PEBDC Ecosystem consists of two parts: capital investment cost C_I and operation & maintenance cost $C_{O\&M}$ for PV, ESS, and chargers as described in equation (1).

$$C_{Total} = C_I + C_{O\&M} \tag{1}$$

As a general rule, $C_{O\&M}$ is assumed to be 10% of the total investment cost [15]. The present worth factor (PWF) [16] is used to transform the total cost into an annualized total present cost shown in equation (2). Where annual real interest rate (r = 6%) = nominal interest rate – inflation rate [17] and N represents the lifetime of ESS, charger, and PV.

$$PWF_{r,N} = \frac{(1+r)^N - 1}{r(1+r)^N} \tag{2}$$

5.2 Objective Function

The objective function is framed as a MILP problem for the daily BDO profit maximization shown in equation (3). "The salvage value is the estimated resale value of an asset at the end of its useful life" which is calculated using the depreciation rate16% for the PV and 40% for ESS and chargers [17]. The salvage value, aggregate investment cost, and PWF of PV, chargers, and ESS are not the same, thus the aggregate daily present cost (recovery) for each one is analysed individually.

$$\frac{profit^{Max}}{day} = \frac{Re\,v^{Max}}{day} - (\frac{\left(C_{total}^{PV} - S_{PV}\right) * PWF_{PV}}{365} + \frac{\left(C_{total}^{ESS} - S_{ESS}\right) * PWF_{ESS}}{365} + \frac{\left(C_{total}^{C} - S_{C}\right) * PWF_{C}}{365}) \tag{3}$$

Where the parameters $S_{PV}, S_C, S_{ESS}, C_{total}^{PV}, C_{total}^{C}, C_{total}^{ESS}, PWF_{PV}, PWF_C\ PWF_{ESS}$ are the salvage value, aggregate investment cost, and present worth factors of the PV, charger, and ESS, respectively. In equation (3) the 1st term indicates the maximized revenue (Rev) produced by BDO each day, 2nd, 3rd, and 4th terms demonstrate the aggregate daily present cost of PV, ESS, and charger, respectively.

The energy exchange is performed between the PEB, building, and grid for 24 hours. The revenue generated each day in time slot *t* is calculated as defined in equation (4) and it depends on the purchasing and selling energy price between ESS2G, PV2G, G2C, C2PEB, PV2B, ESS2B, and G2ESS. Δt which is 10 minutes (resolution time).

$$\frac{Re\,v^{Max}}{day} = Max \sum_{t=1}^{24} \begin{cases} ((P^{PV2G}(t) * C_{Sell}^{2G}(t) + P^{ESS2G}(t) * C_{Sell}^{2G}(t) + P^{PV2B}(t) * C_{Sell}^{2B}(t) \\ + \\ P^{ESS2B}(t) * C_{Sell}^{2B}(t) + P^{PV2C}(t) * C_{Sell}^{2C}(t) \\ + \\ P^{ESS2C}(t) * C_{Sell}^{2C}(t) + P^{C2PEB_{(i)}}(t) * C_{Sell}^{2PEB_{(i)}}(t) \\ - \\ P^{G2C}(t) * C_{Pur}^{from\ G}(t) - P^{G2ESS}(t) * C_{Pur}^{from\ G}(t)) * \Delta t \end{cases} \tag{4}$$

5.3 Design Constraints

Power Balance Constraints: The stable PEBDC Ecosystem indicates that the total power generation and the power consumption should be equivalent at any time interval *t*. The power supplied by the source (ESS, PV, and grid) and demanded by the load (PEB, building, and grid) are represented in equation (5)

$$P_s^{ESS}(t) + P_s^{PV}(t) + P_s^{G}(t) = P_d^{PEB}(t) + P_d^{B}(t) + P_d^{G}(t) \tag{5}$$

ESS Constraints: The maximum and minimum SOC limit is used to preserve the batteries' lifespan [16] which is defined in equation (6). Equations (7-9) correspond to the highest amount of power that the ESS can deliver to the building, charger, and grid, respectively [18, 19]. Equation (10) represents the maximum power that the ESS can take from the grid. As the ESS cannot charge and discharge at the same time, equation (11) correspond to the charging and discharging binary variables. Equations (12) and (13) describe the ESS's charging and discharging threshold, respectively.

$$SOC_{min}^{ESS}(t) \leq SOC^{ESS}(t) \leq SOC_{max}^{ESS}(t) \tag{6}$$

$$P^{ESS2B}(t) \leq P_{max}^{ESS}(t) \tag{7}$$

$$P^{ESS2C}(t) \leq P_{max}^{ESS}(t) \tag{8}$$

$$P^{ESS2G}(t) \leq P_{max}^{ESS}(t) \tag{9}$$

$$P^{G2ESS}(t) \leq P_{max}^{ESS}(t) \tag{10}$$

$$x(t) + y(t) \leq 1\ ;\ x(t), y(t) \in [0,1] \tag{11}$$

$$\left(P_{max}^{ESS}(t) - P_{min}^{ESS}(t)\right) * n_{char} * x(t) \leq \left(P_{max}^{ESS}(t) - P_{min}^{ESS}(t)\right) * y(t) \tag{12}$$

$$\left(P^{ESS2B}(t) + P^{ESS2G}(t) + P^{ESS2C}(t)\right)/n_{dis} \leq \left(P_{max}^{ESS}(t) - P_{min}^{ESS}(t)\right) * x(t) \tag{13}$$

PEB Constraints: The energy safety level, charging limit, SOC update of PEB$_{(i)}$ at any time interval t is defined in equations (14-16) respectively.

$$SOC_{min}^{PEB_{(i)}}(t) \leq SOC^{PEB_{(i)}}(t) \leq SOC_{max}^{PEB_{(i)}}(t) \tag{14}$$

$$\left(P^{C2PEB_{(i)}}(t)\right) * n_{char} \leq \left(P_{max}^{PEB_{(i)}}(t) - P_{min}^{PEB_{(i)}}(t)\right) * y(t) \tag{15}$$

$$SOC^{PEB_{(i)}}(t+1) = SOC^{PEB_{(i)}}(t) + \left(P^{C2PEB_{(i)}}(t)\right) * \Delta t * n_{char} \tag{16}$$

Charger Constraints: The maximum amount of power that chargers can take from the grid, PV, ESS at any time interval *t* is defined in equations (17- 19) respectively. Equation (20) determines the maximum amount of power that a charger can obtain from the ESS, PV, and grid, respectively to charge the PEBs.

$$P^{G2C}(t) \leq \left(P_{max}^{C}(t)\right) \tag{17}$$

$$P^{PV2C}(t) \leq \left(P_{max}^{C}(t)\right) \tag{18}$$

$$P^{ESS2C}(t) \leq \left(P_{max}^{C}(t)\right) \tag{19}$$

$$(P^{ESS2C}(t) + P^{PV2C}(t) + P^{G2C}(t)) * n_{char} \leq \left(P_{max}^{C}(t) - P_{max}^{C}(t)\right) \tag{20}$$

Reverse power flow Constraints: As the ESS, building, grid, and charger, are integrated into the PEBDC Ecosystem, the constraint equations (21-27) are required to prevent reverse power flow.

$$P^{PV2ESS}(t) \geq 0 \tag{21}$$

$$P^{PV2B}(t) \geq 0 \tag{22}$$

$$P^{PV2G}(t) \geq 0 \tag{23}$$

$$P^{PV2C}(t) \geq 0 \tag{24}$$

$$P^{G2B}\,(t) \geq 0 \tag{25}$$

$$P^{G2C}\,(t) \geq 0 \tag{26}$$

$$P^{ESS2B}(t) \geq 0 \tag{27}$$

Solar PV Generation Constraints: The PV generation limit is defined in equation (28) and the balance between the aggregate PV power generation and intake due to (PEBs, Grid, Building, and ESS,) as demonstrated in equation (29).

$$0 \leq P_g^{pv}(t) \leq P_g^{pv}(max)\,(t) \tag{28}$$

$$P^{PV}(t) = P^{PV2G}(t) + P^{PV2ESS}(t) + \; P^{PV2C}(t) + P^{PV2B}(t) \tag{29}$$

Load demand Constraints: Total load demand depends upon the number of PEBs in the PEBDC Ecosystem and total building load. Equation (30) defines the total load boundary limit (building and PEBs) for the proposed model. Where $X_L^{PEB_{(i)}}(t)$, $X_L^B(t)$and $X_L^{total}(t)$ are the load due to $PEB_{(i)}$, building, and the total load at any time interval t. The balance between the aggregate power supply (due to Grid ESS, and PV) and the building load demand is shown in equation (31).

$$0 \leq X_L^{PEB_{(i)}}(t) + X_L^B(t) \leq X_L^{total}(t) \tag{30}$$

$$X_L^B(t) = \left(P^{ESS2B}(t) + P^{PV2B}(t) + P^{G2B}(t)\right) \tag{31}$$

5 Results and Discussions

A simulation has been performed for the energy management of the PEB depot charging ecosystem considering the middle months of all four seasons Summer, Autumn, Winter, and Spring corresponding to January, April, July, and October, respectively. The real-world data from Yutong PEBs [20], Sky Bus's arrival and departure schedule [21], and FITs scheme for the grid [13] are shown in Figure 5 are used in the simulation. Power is purchased from the grid and stored in ESS during low tariffs and is sold back to the grid or to a contracted building at times of high tariff. Overnight charging offers an intelligent and cost-effective solution for both the BDO and PEB owner to charge a large fleet of vehicles during the night-time.

Charging the PEBs during off-peak hours (1:00–6:50 am) can minimize the negative impacts on the power distribution network. Therefore, the price of selling electricity to the PEB is set higher for this period (black line in Figure 5) so that the trading occurs during this period in the simulation.

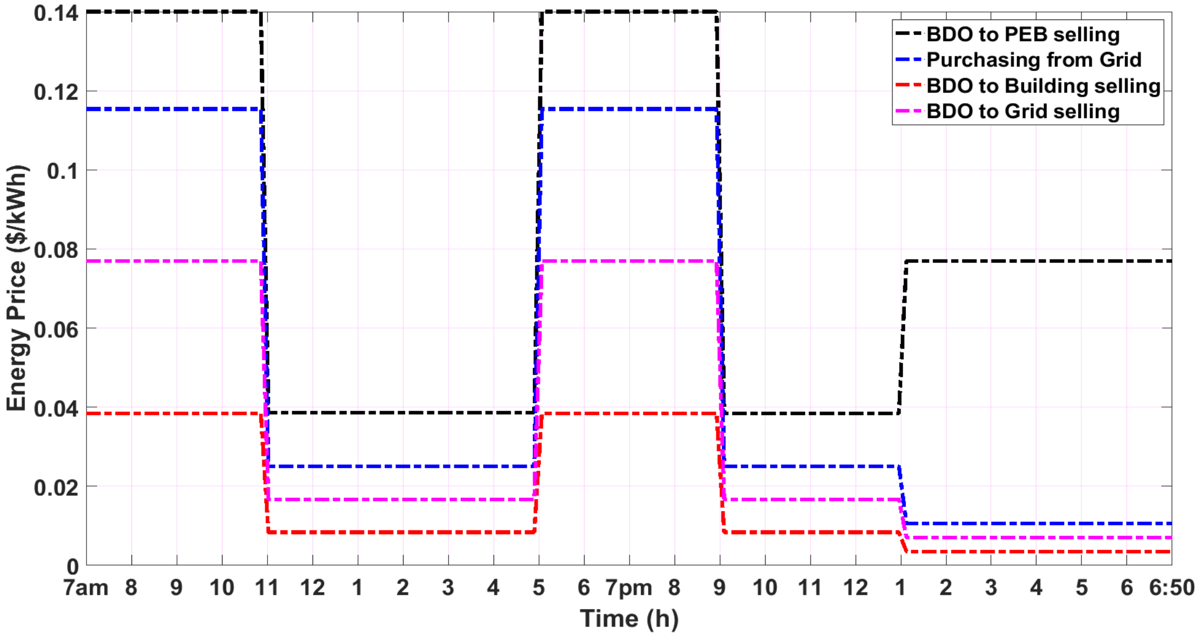

Figure. 5 Proposed FITs scheme for PEBDC Ecosystem.

5.1 Energy trading among PEBDC Ecosystem's agents

Energy trading (selling and buying) among the agents (PV, ESS, Building, PEBs, and grid) in the PEBDC Ecosystem for a whole day for four different seasons namely scenario 1 (summer), scenario 2 (Autumn), scenario 3 (winter) and scenario 4 (spring) are shown in Figure 7, Figure 9, Figure 11, and Figure 13, respectively.

According to the proposed FIT scheme, ESS will charge from the grid when the price on the grid is low and use this energy to charge the PEBs are sell it back to the grid when the price on the grid becomes high. The detailed analysis of each season is as follows.

Scenario 1 (Summer): Figure 6a presents a whole day ESS charging and discharging status. The negative and positive power values on the y-axis correspond to the ESS charging from grid/PV and discharging from ESS to grid/building/PEBs, respectively. The SOC of ESS is updated in each time interval *t* as shown in equation (32).

$$SOC^{ESS}(t+1) = SOC^{ESS}(t) + \left(P^{G2ESS}(t) + P^{PV2ESS}(t)\right) * \Delta t * n_{char} \\ - \left(P^{ESS2G}(t) + P^{ESS2B}(t) + P^{ESS2C}(t)\right) * \Delta t / n_{dis} \tag{32}$$

The building and grid offer a high price from (7:00-11:00 am) thus, ESS sells power to the building and grid. However, ESS is charging again for the time interval (11:00-5:00 pm) from grid and PV for upcoming use. During the time interval (6:00-9:00 pm) some of the available power in the ESS is sold to the grid and the rest is used to charge PEB1 and PEB6 from (7:10–9:00 pm) respectively. Two PEBs (PEB1 and PEB6) arrived at the depot at 7:00 pm, and 7:50 pm, respectively [21] charged using ESS. However, PEB12 which arrived at 9:00 is not charged using the PV or ESS. This is because of the unavailability of PV energy and ESS is charging at the arrival of PEB12 (ESS charging and discharging cannot occur at the same time to preserve the battery lifespan). Once More from (9:00 pm - 6:50 am), the ESS is charging from the PV and grid (if available) to fully charge the ESS for the next day's use. The balance between the consumption (due to, Grid, ESS, PEBs, and Building) and aggregate PV power production and is calculated using equation (29) and the result is demonstrated in Figure 6b.

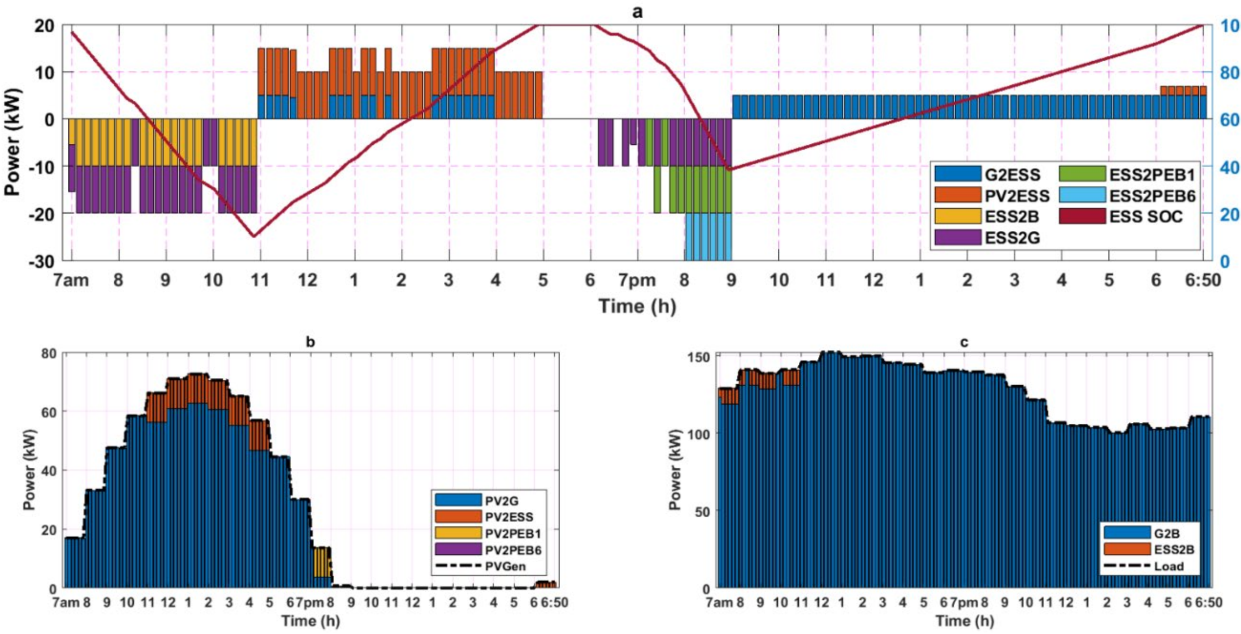

Figure 6 a) ESS SOC in a single day; b) PV Supply and Production c) Power Supply and Building Load Demand (Summer).

To decrease the burden on the distribution feeder due to higher building energy intake arising from grown urbanization, the stored power in ESS is utilized to provide power to the building when it is available. The balance between the total power supply (due to PV, ESS, and Grid) building load demand and is performed using equation (31), and the result is demonstrated in Figure 6c.

Figure 7a and Figure 7b show the amount of power provided by ESS to (building (B), Grid (G), and PEBs) and PV to (G, ESS, and PEBs) respectively for the summer season. It is interesting to note that only 1% of PV generated power is utilized to charge the PEBs as shown in Figure 7b. The reason is the 1st and 2nd PEBs are arriving at 7:00 and 7:10 pm respectively and the PV generation is available until 8:00 pm. Therefore, PV to PEBs charging occurs for the time interval 7:10 pm – 8:00 pm.

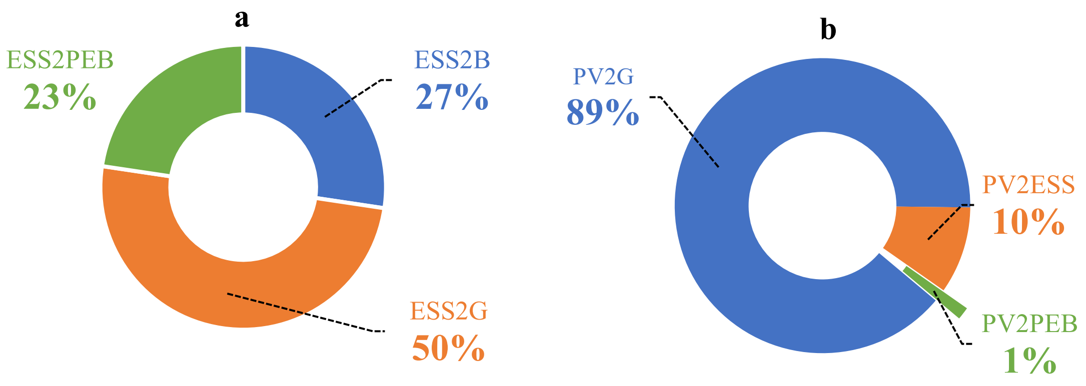

Figure 7 Power provided by a) ESS to B, G, and PEBs; b) PV to B, G, and PEBs (Summer).

Scenario 2 (Autumn): In accordance with the FITs scheme, the PV produced power is exported back to the grid or traded to the PEBs/ building. Figure 8a shows a single day ESS charging and discharging status, PV generation, and building load demand and supply for the Autumn season. As compared to summer, the PV power generation is only for the time interval 8:00 am - 6:50 pm which is half for the autumn season as can be seen in Figure 8b. In New Zealand, Autumn months temperatures are cooler than summer, therefore the building load demand (due to hot water usage) for the Autumn season is slightly higher than summer and this is served by the grid the ESS (see Figure 8c).

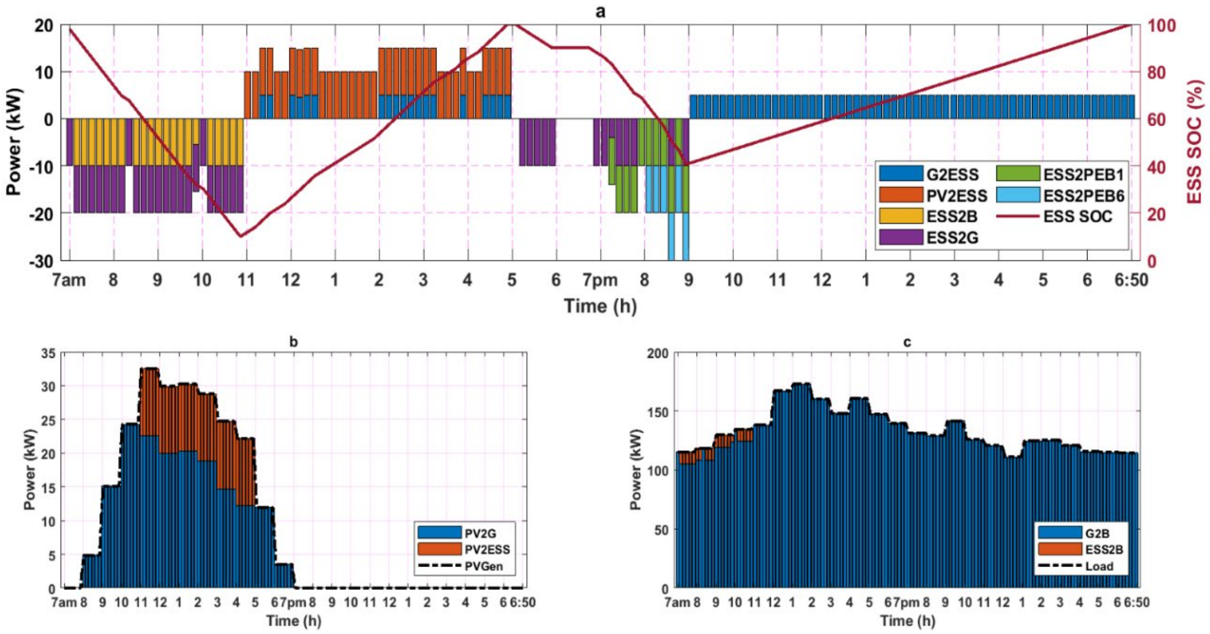

Figure 8 a) ESS SOC in a single day; b) PV Supply and Production c) Power Supply and Building Load Demand (Autumn).

Figure 9a and Figure 9b show the amount of power provided by ESS to (B, G, PEBs) and PV to (G, ESS, and PEBs) for the autumn. It is interesting to note that the PV generation in autumn does not match with the PEB arrival therefore, the energy trading between PV to PEB is zero. However, ESS is selling the stored power to grid, building, and PEBs which is 49%, 28%, and 23% respectively as can be seen in Figure 9a. The power generated by PV is selling to Grid and ESS which is 74% and 26% respectively shown in Figure 9b.

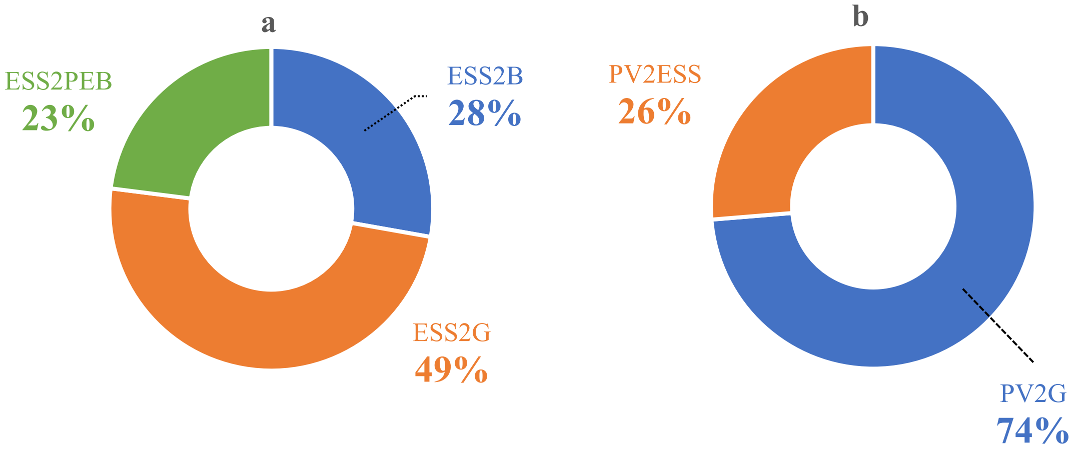

Figure 9 Power provided by a) ESS to B, G, and PEBs; b) PV to B, G, and PEBs (Autumn).

Scenario 3 (Winter): A single-day ESS charging and discharging status, PV generation, and building load demand and supply for the winter season is shown in Figure 10a. In winter, the sun is lower in the sky and hence there is limited PV power generation and only for the time interval 9:00 am - 6:00 pm. Thus, the generation is much less compared to the other three seasons as can be seen in Figure 10b. Moreover, in winter, due to the cold weather, there is more electricity usage (due to hot water) therefore, the building load demand in the winter season is higher than for any other season. This building load demand is served by the grid and ESS (see Figure 10c).

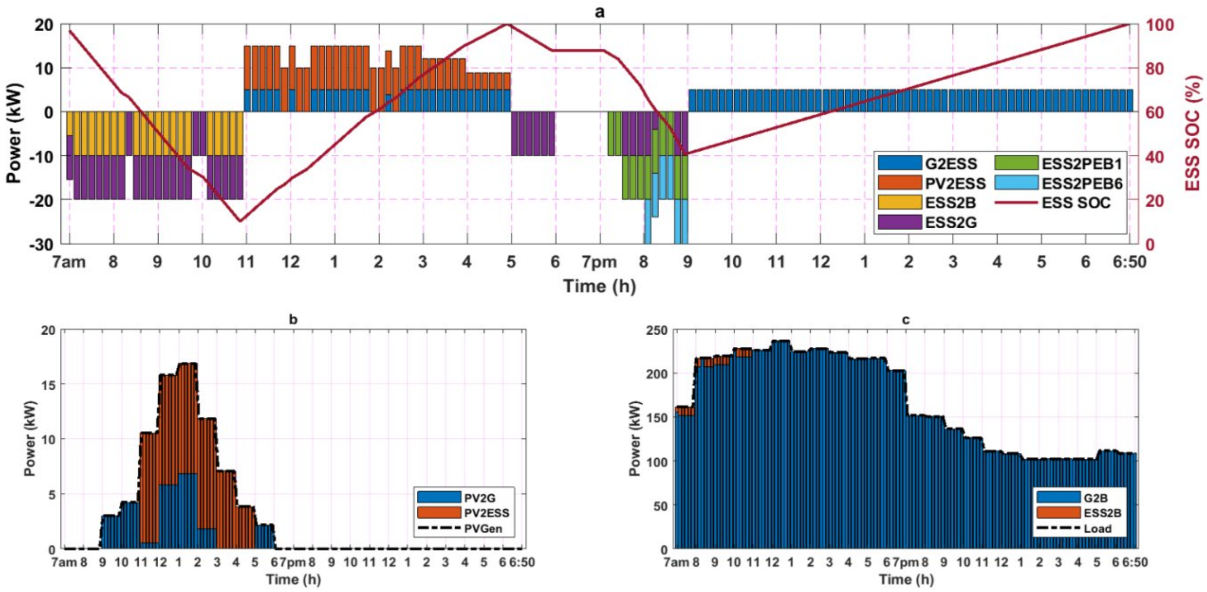

Figure 10 a) ESS SOC in a single day; b) PV Supply and Production c) Power Supply and Building Load Demand (Winter).

Figure 11a and Figure 11b show the amount of power provided by ESS to (B, G, PEBs) and PV to (G, ESS, and PEBs) for the winter season. Similar to the autumn season, the PV generation does not match with the PEB arrival therefore, energy trading between PV to PEB is zero.

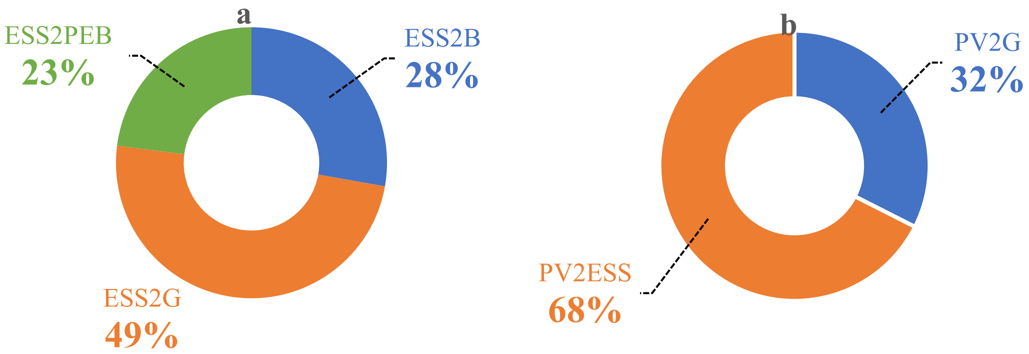

Figure 11. Power provided by a) ESS to B, G, and PEBs; b) PV to B, G, and PEBs (Winter).

Scenario 4 (Spring): Figure 12a shows a single-day ESS charging and discharging status, PV generation, and building load demand and supply for the winter season. In the spring season, the PV power generation is much higher than in autumn and winter (7:00 am - 7:00 pm). The power generation can be seen in Figure 12b. Furthermore, the building load demand for the spring season is lower than in winter and autumn due to less electricity usage (more specifically less hot water usage). This demand is served by the grid and ESS (see Figure 12c).

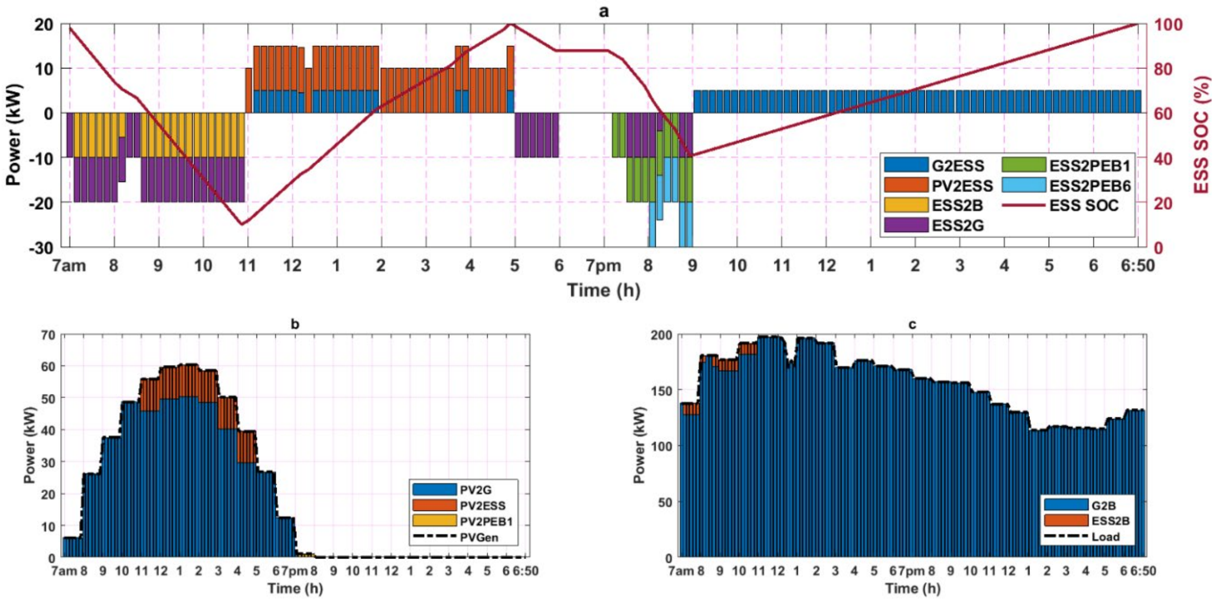

Figure 12. a) ESS SOC in a single day; b) PV Supply and Production c) Power Supply and Building Load Demand (Spring).

Figure 13a and Figure 13b show the amount of power provided by ESS to (building, grid and, PEBs) and PV to (grid, ESS, and PEBs), respectively for the spring season. ESS sells the stored power to the grid, building, and PEBs which is 49%, 28%, and 23%, respectively as can be seen in Figure 13a. Similar to autumn and winter, in the spring season, the PV generated power does not match with the PEB arrival thus, the energy trading between PV to PEB is zero. However, ESS used 13% of PV generation and the rest of 87% is sold to the grid.

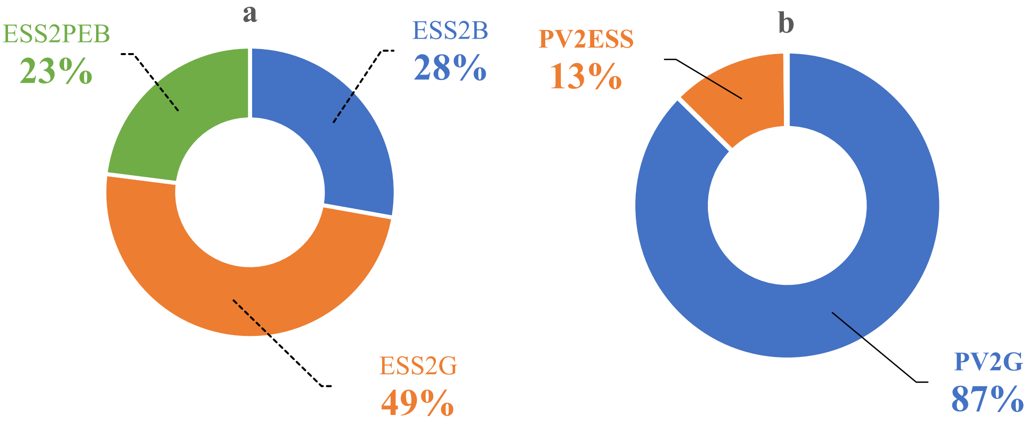

Figure 13. Power provided by a) ESS to B, G, and PEBs; b) PV to B, G, and PEBs (Spring).

It is interesting to note that the winter season has less profit and the summer season has the highest profit. The daily profits gained by BDO during each season with EMS and without EMS are shown in Table 2. It is also interesting to note that the profit made by the BDO without EMS is fixed for all four seasons. However, with EMS the profit for the different seasons e.g., summer, spring, autumn, and winter are 68%, 58% 36%, and 11.46% respectively.

Table 2 Daily Seasonal Profit (NZ$)

Seasons	**Months**	**Profit with EMS**	**Profit without EMS**
Summer	January	231.684	75.9885
Spring	October	181.196	75.9885
Autumn	April	119.781	75.9885
Winter	July	85.8222	75.9885

6 Conclusion

This paper presents an efficient energy management system for the PEBDC ecosystem integrated with an LV Feeder. The key findings of this paper are as follows:

i) The proposed cost-efficient energy management system is based on a double-sided auction mechanism that provides a platform to perform energy trading among the selling and buying agents in the PEBDC ecosystem. It is important to note that energy usage varies from region to region. However, in this study, we only consider the location of Auckland Airport, New Zealand.

ii) A simulation has been performed for the energy management of the PEB depot charging ecosystem considering the middle months of all four seasons Summer, Autumn, Winter, and Spring corresponding to January, April, July, and October, respectively.

iii) A MILP model in CPLEX is developed considering the capital investment, operation & maintenance, and depreciation costs for installing PV, ESS, and chargers. The objective of the developed mathematical model is to maximize the daily profit of the BDO owner by performing energy trading among the selling agents (PV, ESS (discharge), grid), and purchasing agents (grid, ESS (discharge), PEBs). The energy trading and the daily profit are analyzed for all four seasons.

iv) Real-world data from SkyBus arrival and departure schedule, Yutong PEBs, FITs scheme for the grid, and the load of one of Auckland University of Technology campus buildings (load demand (AC) for all four seasons Summer, Autumn, Winter, and Spring shown in Figures 6, 8, 10, and 12, respectively) is used. The constraints such as power balance, ESS, PEB, grid, charger, PV, generation, and demand are considered in the simulation.

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