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Evaluating the Role of Integrated Photovoltaic and Energy Storage Systems in the Net-Zero Transition: A Case Study in Taiwan

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Abstract: This study investigates the role of integrated photovoltaic and energy storage systems in facilitating the net-zero transition for both governments and consumers. A bi-level planning model is proposed to address the challenges encountered by existing power supply systems in meeting the escalating electricity demands. In the upper level, governments provide incentives to users through subsidies for photovoltaic power generation, energy storage system installations, and electricity procurement. Meanwhile, at the lower level, load requirements are optimized, and costs are minimized by integrating solar power generation, battery energy storage, and electricity procurement. To effectively address these complexities, a hybrid physics-inspired algorithm for bi-level programming is utilized for iterative problem solving. The findings indicate that relying on photovoltaic output during peak load periods and conducting small electricity purchases, while storing excess electricity, proves to be an efficient approach. This model offers a cost-effective solution for managing energy consumption, mitigating potential power shortages, and reducing frequent outages. Furthermore, this research contributes to a comprehensive understanding of the net-zero transition and its implications for power supply systems. Specifically, it highlights the significance of integrated photovoltaic and energy storage systems in assisting businesses with specific energy storage planning, determining optimal charging and discharging schedules, and considering government subsidies.

Keywords: energy storage; optimization; photovoltaic system; bi-level programming; subsidy

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1. Introduction

Worldwide, the rise in energy prices fueled by factors such as oil, natural gas, and coal has led to a gradually worsening shortage of power supply. Despite electricity price increases, electricity consumption continues to grow steadily. As a result, controlling electricity consumption and promoting energy self-sufficiency have become critical concerns for governments and experts.

To address high electricity demands, we propose integrating solar power, the grid, and energy storage systems for an optimized strategy for consumers. Taiwan has experienced substantial uptake of solar power, harnessing its plentiful solar resources. This approach extends beyond utility-scale installations to encompass residential, commercial, and agricultural sectors. According to the Energy Transition Promotion Scheme, Taiwan aims to install 20 GW of solar photovoltaic (PV) power by 2025, with 17 GW on the ground and 3 GW on rooftops [1]. As of May 2023, solar PV accounted for 69.0% of total renewable capacity, contributing 6.9% of overall power generation [2]. To achieve net-zero carbon emissions, as of 2021, the implementation of the "Large Electricity Consumers" provision in Taiwan necessitates that electricity consumers with contract capacities exceeding 5000 kW must obtain 10% of their electricity from renewable energy sources within a five-year timeframe, impacting around 300 companies [3]. Nonetheless, the adoption of energy storage by businesses under this provision is limited to approximately 3% due to the relatively higher costs involved. However, this lack of uptake can be attributed to businesses not fully recognizing the substantial contribution of energy storage to maintaining power balance and stability. As a result, there is an urgent demand for a comprehensive scientific study to offer businesses comprehensive planning insights. To encourage broader adoption of green energy, including lithium battery storage, subsidies or incentives can be implemented, leading to an increase in the utilization of renewable energy sources. The popularity of lithium batteries is primarily due to their high capacity and energy density, aligning with the government's objective of achieving net-zero emissions.

The prominence of battery energy storage is growing, as it offers optimal efficiency in energy capacity and power density. While Taiwan's battery industry has developed more slowly, prominent manufacturers are actively engaged in research and development [4]. With support from neighboring countries/regions and leveraging Taiwan's industrial strength, the industry holds growth potential. To address Taiwan's power challenges, we propose promoting the adoption of PV energy storage systems by companies and households for partial self-sufficiency. This approach effectively mitigates the power shortage while capitalizing on the strengths of the lithium battery industry and technical collaborations with neighboring countries/regions.

Given the current power situation and technological capabilities in Taiwan, the integration of PV and lithium battery energy storage systems provides a viable solution to address power challenges. Our analysis aims to develop an information system to increase public awareness and willingness to adopt PV storage systems. Achieving energy self-sufficiency is crucial to mitigate the impact of rising energy prices on people's daily lives.

To achieve our objectives, we propose a bi-level programming model for government and consumers. The upper-level model focuses on developing a subsidy strategy to increase user acceptance. Due to budget constraints, the upper-level model is subject to a limit on the total subsidy budget set by the government. The lower-level model aims to optimize user-side systems under government subsidies, minimizing annual electricity costs. This includes determining the installation capacity of PV and energy storage systems, charging and discharging periods, and the user's electricity procurement strategy. The lower-level model incorporates basic constraints, such as limiting energy storage charging to available capacity and ensuring supply meets demand. Additional constraints are designed to encourage user responsiveness to environmental concerns, including limiting power wastage, reducing carbon emissions, and promoting PV generation and the use of green energy in the overall supply. The research framework is illustrated in Figure 1.

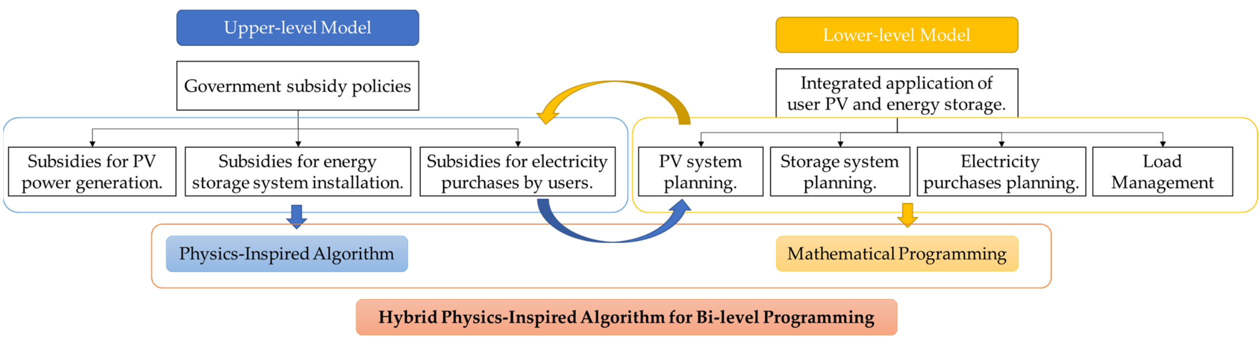


Figure 1. Framework diagram for bi-level problem of integrated PV and energy storage.

2. Literature Review

When conducting year-round PV power generation, two important issues arise: seasonal and temporal considerations, as mentioned in reference [5]. The first issue pertains to the relationship between seasonal electricity generation and consumption. In regions like Taiwan, electricity usage spikes during the summer season due to increased demand for air conditioning in households and commercial buildings to combat the heat. As a result, electricity consumption is significantly higher compared to the winter season. To address this, the Taiwan Power Company has implemented various electricity pricing schemes to curb the rising demand during summer. The second issue relates to the correlation between daytime and nighttime electricity consumption. Typically, the peak pricing period for daily electricity usage occurs between 7:30 a.m. and 10:30 p.m. During this period, the implementation of battery energy storage systems (BESS) can effectively reduce the peak load of the day [6]. These two issues form the focal point of this study, which aims to establish a mathematical model that reduces reliance on the main power grid through the implementation of PV power generation. This approach aims not only to reduce costs but also to decrease dependence on fossil-fuel-based power generation.

Reference [7] emphasizes the significance of distributed PV energy storage systems, which combine PV generation and energy storage. These systems effectively reduce consumer reliance on utilities and enhance their ability to prevent energy disruptions during PV generation. This insight inspires us to establish constraints in our study, enabling consumers to support critical loads and meet their energy needs during system failures, ensuring power service maintenance, and improving system reliability. Furthermore, reference [8] validates the technical and economic feasibility of connecting numerous households with BESS and PV in a distribution network. Through simulation, a new three-tier time-of-use (TOU) tariff is introduced, effectively increasing response frequency while minimizing the impact on residents' lifestyle.

Ensuring the reliable operation of energy storage systems requires stable power input and output and sufficient energy storage capacity. Battery lifespan significantly affects the cost of PV power generation systems, and factors such as unstable current, abrupt charging, and excessive discharge can impact battery life, as highlighted in reference [9]. Proper balancing of voltage and current characteristics is crucial when multiple batteries are employed in energy storage systems. Considering these factors, energy storage systems can provide positive benefits in terms of both economic and system stability aspects when operated at appropriate charging and discharging frequencies. Furthermore, reference [10] introduces an optimization model for community energy markets that incorporates BESS to increase community income. The model assesses BESS degradation, explores different arrangements, and evaluates feasibility based on social welfare and fairness indicators, providing valuable insights into the impact of BESS within energy communities. In addition, reference [11] emphasizes the positive impact of integrating electricity storage systems into electrical networks, enhancing the stability of primary generators and improving overall system safety and reliability.

Reference [5] proposes an efficient energy storage strategy to minimize daily power purchase costs, while reference [12] introduces a bi-level programming model to further optimize energy storage systems. These models determine appropriate capacities and charging/discharging strategies for PV and energy storage systems. It is worth noting that the optimization in reference [12] is based on monthly representation, which may deviate from real-world scenarios. Integration of an inherited competitive swarm optimization (ICSO) algorithm in reference [13] optimizes the location, capacity, and dispatches of a BESS in an unbalanced distribution network. Reference [14] proposes a multi-objective methodology for BESS allocation in distribution networks, utilizing a new node voltage sensitivity analysis strategy and genetic algorithm (GA). In related studies, reference [15] employs the GA for BESS allocation in radial distribution networks with solar power, while reference [16] uses particle swarm simulation for distributed PV integration, load demand optimization, and PV storage partition planning. These approaches consider various cost considerations and energy management methods to ensure a rationalized and realistic mathematical model.

Furthermore, inventory models in supply chain management can serve as a basis for discussions on energy storage, as energy storage is essentially the storage of the product "energy" and can be modelled in a similar way. The concepts of economic production quantity (EPQ) and joint economic lot sizing were incorporated into energy management systems to determine the supply and production strategies of the energy system in reference [17]. It can be found that optimization techniques, combined with the concept of inventory management, can be used for energy storage capacity assessment.

In conclusion, the integration of solar PV and energy storage systems provides advantages in terms of economic benefits and system stability. To enhance practical cost optimization, a more detailed approach considering time periods and cost elements can be implemented, incorporating inventory management models and frameworks. Furthermore, the utilization of a bi-level planning model, coupled with algorithms, enables the exploration of multi-agent cooperation and resolves problem-solving difficulties.

3. Bi-Level Programming Model

This study utilizes a bi-level programming model to optimize the integration of PV and energy storage systems for government and consumers. The upper-level model aims to minimize the total subsidy amount, with its decision variables serving as input parameters for the lower-level model. The objective of the lower-level model is to minimize annual electricity costs for users under the subsidy policy, considering the use of integrated PV and energy storage systems. Some of the decision variables in the lower-level model are used as input parameters for the upper-level model. In this optimization solution model, the amount of data considered is 366 days per year, with each day's data divided into intervals of 1 h and represented by 24 data points per day. Below, we will discuss the notations of parameters and variables, objective functions, and constraints for both the upper- and lower-level models in Table 1.

Table 1. Notations and definitions used in the bi-level programming modelling.

Symbol	Definitions
	Set
m	Number of months→$m \in \{1, 2, \ldots, 12\}$
d	Number of dates→$d \in \{1, 2, \ldots, 31\}$
h	Number of hours→$h \in \{1, 2, \ldots, 24\}$
	Common Parameters
N_m	Number of natural days in month m
Bu	Government subsidy budget cap for users (based on user size)
Eu	The carbon emission cap for users (based on user size) set by the government
Wu	Annual excess electricity cap for users (based on user size)
Ch	Holding cost of electricity stored in the energy storage system
Cp	Cost of power generation by the PV system
Cc	Cost of the energy storage system charging
Ep	The carbon emissions per unit of purchased electricity generated by users
β	Discharge efficiency of the energy storage system
$P_{m,d,h}$	Purchasing price of power according to different types of power users in month m, date d, hour h
$\theta_{m,d,h}$	The capacity factor of PV power generation in month m, date d, hour h
$Load_{m,d,h}$	User load to be satisfied in month m, date d, hour h
	Upper-level Decision Variables (Government)
Spv	The subsidy amount per unit of electricity generated by the PV system (Input for lower level)
$Sbat$	The subsidy amount per unit of capacity installed for the energy storage system(Input parameter for lower level)
Sp	The subsidy amount per unit of purchased electricity (option, default is 0/if there are subsidies for conventional power generation) (Input parameter for lower level)
	Lower-level Decision Variables (User)
$Ebat$	Battery capacity of the energy storage system (Input parameter for upper level)
Epv	PV system installed capacity
$Cha_{m,d,h}$	Charging electricity of the energy storage system in month m, date d, hour h
$DCh_{m,d,h}$	Discharging electricity of the energy storage system in month m, date d, hour h
$Inv_{m,d,h}$	Ending inventory of energy storage system in month m, date d, hour h
$PV_{m,d,h}$	PV output in month m, date d, hour h (Input parameter for upper level)
$Pu_{m,d,h}$	Electricity purchased by user in month m, date d, hour h (Input parameter for upper level)

In this paper, certain parameter values are assumed to be universal for the purposes of the example. Specifically, we assume that January, March, May, July, August, October, and December consist of 31 natural days, while April, June, September, and November consist of 30 natural days, and February consists of 28 or 29 natural days. Furthermore, we set the values of Ch, Cp, Cc, and β to 0.5, 5, 10.6, and 0.9, respectively. As the values of $P_{m,d,h}$, $\theta_{m,d,h}$, and $Load_{m,d,h}$ vary depending on the specific user, no universal values were assigned to these parameters.

3.1. Upper-Level Model

The upper-level objective is to minimize the total subsidy amount, which includes subsidies for PV generation, energy storage system installation, and purchased electricity. Therefore, the upper-level objective function is shown in Equation (1).

$$Minimize\ Z_U = Spv \sum_{\forall m,d,h} PV_{m,d,h} + Sp \sum_{\forall m,d,h} Pu_{m,d,h} + Sbat \times Ebat \tag{1}$$

- Total subsidy amount constraint

Considering that the government is likely to have budget constraints when implementing subsidy policies, we assume a specific user subsidy budget of Bu per year. The corresponding constraint is shown in Equation (2).

$$Spv \sum_{\forall m,d,h} PV_{m,d,h} + Sp \sum_{\forall m,d,h} Pu_{m,d,h} + Sbat \times Ebat \leq Bu \tag{2}$$

- Annual PV generation as a percentage of the user's annual load constraint

To ensure effective utilization of the PV system by users, this study assumes that the government promotes a policy target for commercial users to set their PV generation as a percentage of their annual load, with a minimum requirement of 40%. The corresponding constraint is shown in Equation (3).

$$Spv \sum_{\forall m,d,h} PV_{m,d,h} \geq 0.4 \times \sum_{\forall m,d,h} Load_{m,d,h} \tag{3}$$

- Carbon emissions constraint

In response to rising environmental awareness, the government will impose annual carbon emission limits on specific users, assuming that their carbon emissions from purchased electricity do not exceed Eu. The remaining electricity demand must be met by solar PV and energy storage. The constraint is defined as Equation (4).

$$\sum_{\forall m,d,h} Pu_{m,d,h} \times Ep \leq Eu \tag{4}$$

The upper-level constraint still includes non-negativity constraints on decision variables, Spv, $Sbat$, and Sp. The upper-level model aims to consider achieving specific government objectives through minimal subsidy amounts. However, apart from the subsidy amount, the solar power generation, energy storage capacity, and user electricity purchasing are not determined by the government. Therefore, to determine whether the objectives are met, the subsidy amount needs to be inputted into the lower-level user model for calculation.

3.2. Lower-Level Model

The lower-level objective is to minimize the annual comprehensive cost under the subsidy amount. The cost items include the charging cost and holding cost of the energy storage system, the cost of PV power generation, and the cost of the user's self-purchased electricity. The subsidy items include subsidies for PV power generation, energy storage system installation capacity, and electricity purchase. Therefore, the objective function is shown in Equation (5).

$$Minimize\ Z_L = \sum_{m=1}^{12} \sum_{d=1}^{N_m} \sum_{h=1}^{24} \Big[(CcCha_{m,d,h}) + (ChInv_{m,d,h}) + \Big(CpPVout_{m,\ d,\ h} \Big) + (P_{m,d,h} Pu_{m,d,h}) \Big] - Z_U \quad (5)$$

- PV power generation constraint

The PV system does not generate electricity continuously throughout the day. The PV power generation in each time period should be equal to the installed capacity of the PV system multiplied by the PV capacity factor for each time period. The constraint is defined as Equation (6):

$$PV_{m,d,h} = \theta_{m,d,h} Epv, \forall\ m,\ d,\ h \quad (6)$$

- Supply must meet demand all the time

This model considers the supply to consist of the output of the PV system, the discharge from the energy storage system, and the purchased power, while the demand includes the user load and energy storage charging. The total supply in this model must be greater than or equal to the total demand, which can be mathematically expressed using the constraint formula shown in Equation (7).

$$PV_{m,d,h} + DCh_{m,d,h} + Pu_{m,d,h} \geq Load_{m,d,h} + Cha_{m,d,h}, \forall\ m,\ d,\ h \quad (7)$$

- The output of PV power generation and energy storage system must satisfy the user's hourly partial load

Given the growing need for net-zero transition, an increasing number of businesses and individuals are strengthening their capacity to utilize green energy for self-consumption. This is accompanied by declarations of net-zero goals and participation in initiatives like RE100. Taking this into consideration, the present study recognizes this constraint as an opportunity to encourage users to progressively enhance their utilization of renewable energy devices. Consequently, this constraint serves as a primary research focus. To ensure power supply during periods without sunlight, the energy storage system needs to be discharged, regardless of the discharge cost, when there is no output from the PV system. Additionally, when the PV system is generating power, it is necessary to ensure that the combined output of both systems meets certain requirements, such as a 20% load in this model. The constraint is defined as Equation (8).

$$DCh_{m,d,h} + PV_{m,d,h} \geq 0.2 Load_{m,d,h}, \forall\ m,\ d,\ h \quad (8)$$

- The ending inventory in the energy storage system should be continuous

To maintain the consistency of the final inventory, it is crucial to restrict its fluctuations. To ensure energy conservation, the ending inventory of the current period must be equivalent to the previous period's ending inventory plus the current period's charging amount minus the discharging amount. To satisfy this constraint, the initial battery capacity inventory is assumed to be completely charged. Additionally, when programming, it is essential to consider the variations in index values due to the differences in natural days between months. This constraint is defined as Equation (9).

$$\begin{array}{ll} Inv_{m,d,h} \leq Ebat - (DCh_{m,d,h}/\beta), & m = d = h = 1; \\ Inv_{m,d,h} \leq Inv_{m,d,h-1} + Cha_{m,d,h} - (DCh_{m,d,h}/\beta), & d \neq 1;\ h \neq 1;\ \forall\ m \\ Inv_{m,d,h} \leq Inv_{m,d-1,24} + Cha_{m,d,h} - (DCh_{m,d,h}/\beta), & d \neq 1;\ h = 1;\ \forall\ m \\ Inv_{m,d,h} \leq Inv_{m,N_{m-1},24} + Cha_{m,d,h} - (DCh_{m,d,h}/\beta), & d = 1;\ h = 1;\ \forall\ m \end{array} \quad (9)$$

- The charging amount of the energy storage system constraint

In consideration of the fixed energy storage capacity, it is necessary to restrict the charging amount to ensure that it does not exceed the available space. That is to say, the capacity of the energy storage battery is used to deduct the inventory at the end of the previous period and the discharge of the energy storage system in the current period to know how much remaining space is available for the energy storage system to charge. The constraint is defined as Equation (10).

$$\begin{array}{ll} Cha_{m,d,h} \leq DCh_{m,d,h}, & m = d = h = 1 \\ Cha_{m,d,h} \leq Ebat - Inv_{m,d,h-1} + DCh_{m,d,h}, & d \neq 1;\ h \neq 1;\ \forall\ m \\ Cha_{m,d,h} \leq Ebat - Inv_{m,d-1,24} + DCh_{m,d,h}, & d \neq 1;\ h = 1;\ \forall\ m \\ Cha_{m,d,h} \leq Ebat - Inv_{m,N_{m-1},24} + DCh_{m,d,h}, & d = 1; h = 1;\ \forall\ m \end{array} \tag{10}$$

- The discharging amount of the energy storage system constraint

From an engineering standpoint, it is crucial to limit the discharge capacity of the energy storage system to avoid releasing more energy than the remaining capacity inside the battery. Moreover, the discharge efficiency must also be taken into account. In situations where the PV system has no output, it becomes necessary to discharge the energy storage system. Therefore, the discharge capacity is subject to the following limitation formula, as shown in Equation (11).

$$\begin{array}{ll} DCh_{m,d,h} \leq \beta \times Ebat, & m = d = h = 1 \\ DCh_{m,d,h} \leq \beta \times Inv_{m,d,h-1}, & d \neq 1;\ h \neq 1;\ \forall\ m \\ DCh_{m,d,h} \leq \beta \times Inv_{m,d-1,24}, & d \neq 1;\ h = 1;\ \forall\ m \\ DCh_{m,d,h} \leq \beta \times Inv_{m,N_{m-1},24}, & d = 1;\ h = 1;\ \forall\ m \end{array} \tag{11}$$

- The battery capacity of the energy storage system constraint

In order to meet the inventory requirements at the end of each period, it is crucial to ensure that the capacity of the energy storage battery is sufficient. This consideration is essential to avoid any shortfall in energy supply and maintain the stability of the system. The constraint is defined as Equation (12).

$$Ebat \geq \max\{Inv_{m,d,h}\} \forall\ m,\ d,\ h \tag{12}$$

- Annual Excess Electricity Limit

For users, if the proportion of self-consumption of renewable energy is high, it will lead to excessive supply and further waste of electricity. Although the excess electricity can be fed into the grid in practice, in order to effectively plan the appropriate amount of PV installations, this study limits the annual excess electricity to less than Wu, and the constraint is defined as Equation (13).

$$\sum_{\forall m,d,h} \left(PV_{\ m,d,h} + DCh_{m,d,h} + Pu_{m,d,h}\right) - \sum_{\forall m,d,h} \left(Cha_{\ m,d,h} + Load_{m,d,h}\right) \leq Wu \tag{13}$$

The lower-level constraint still includes non-negativity constraints on decision variables, $Ebat$, Epv, $Cha_{m,d,h}$, $DCh_{m,d,h}$, $Inv_{m,d,h}$, $PV_{m,d,h}$, and $Pu_{m,d,h}$. The lower-level model decides the amount of solar PV and energy storage installations based on the concept of cost minimization after the government subsidy amount decision of the upper-level model is given. Generally, such bi-level models pose a non-smooth optimization problem, since the optimal value function is not differentiable in general. Heuristic methods constitute one effective approach in this case.

4. Hybrid Physics-Inspired Algorithm for Bi-Level Programming

In reference [18], the Bi-level Centers Algorithm (BCA), a physics-inspired algorithm based on the center of mass concept, was successfully used as the lower-level optimizer for solving bi-level optimization problems. By considering the objective function values of randomly selected solutions, the algorithm generates new directions in the continuous search space of the hierarchical optimization structure. However, considering the reduced complexity resulting from fewer decision variables and constraints in our upper-level model, we will utilize the physics-inspired algorithm to solve it. The feasible solutions obtained from this process will then be used as inputs for the lower-level model, which will be solved using the Gurobi optimization solver.

4.1. Physics-Inspired Algorithm

The physics-inspired algorithm first generates a population set P of N solutions, where $N = K \times D$. Here, K represents the input parameters, and D represents the number of decision variables in the planning model. For each solution in the set, a heuristic algorithm is applied, and the iteration stops when the objective function value of the approximate optimal solution converges to a minimal error. The algorithm steps are described as follows [18]:

1. A subset U is extracted from the population set P, where $U \in P$.
2. The centroid vector $\vec{c_i}$ is calculated using the formula shown in Equation (14).

$$\sum_{i=1}^{K} m(\vec{u_i})(\vec{u_i} - \vec{c_i}) = 0, \text{implies } \vec{c_i} = \frac{1}{M}\sum_{i=1}^{K} m\left(\vec{u_i}\right)\vec{u_i} \tag{14}$$

   Here, $m\left(\vec{u_i}\right)$ represents the mass of $\vec{u_i}$, which is the value of the objective function, and M is the sum of the masses of the vectors in U.
3. Identify the solution with the worst performance in the subset, denoted as $\vec{u}_{worst}$, which corresponds to the worst value of the objective function. Use the formula shown in Equation (15) to calculate an updated solution $\vec{q_i}$:

$$\vec{q_i} = \vec{y_i} + \eta_i\left(\vec{c_i} - \vec{u}_{worst}\right) \tag{15}$$

   $\vec{y_i}$ represents the current solution, and η_i is a random number.
4. After calculating the updated solution, substitute it into the objective function and check if it outperforms the current solution. If the updated solution is better, replace the current solution with the updated one.
5. After performing calculations for each solution in the population set, update the size of the population using the formula shown in Equation (16).

$$N(t) = KD - \frac{(KD - 2K)t}{T} = K\left(D - \frac{(D-2)t}{T}\right) \tag{16}$$

   Here, t represents the current iteration number, and T denotes the maximum number of iterations, which is user-defined.
6. Once the algorithm has been applied to each solution in the population set, evaluate whether the objective function values of the best solution in the original population set and the best solution in the current iteration have converged to a minimal error. If convergence is achieved, terminate the iteration; otherwise, proceed with further iterations of the algorithm.

4.2. Hybrid Algorithm for Bi-Level Programming

The physics-inspired algorithm mentioned in reference [18] is used to generate an initial set of solutions for the lower-level model using random values. However, given the large number of decision variables in the lower-level component of our planning model and the presence of partially zero values in optimal solutions for time-dependent decision variables, we have determined that the algorithm described is not entirely suitable for solving the lower-level model in our current problem. Conversely, our upper-level model only involves three decision variables, making the physics-inspired algorithm more suitable for iterative solving. To address the unique characteristics of the lower-level model, we will utilize the Gurobi optimization solver to solve the mathematical model. Figure 2 illustrates the step-by-step solution process for this approach.

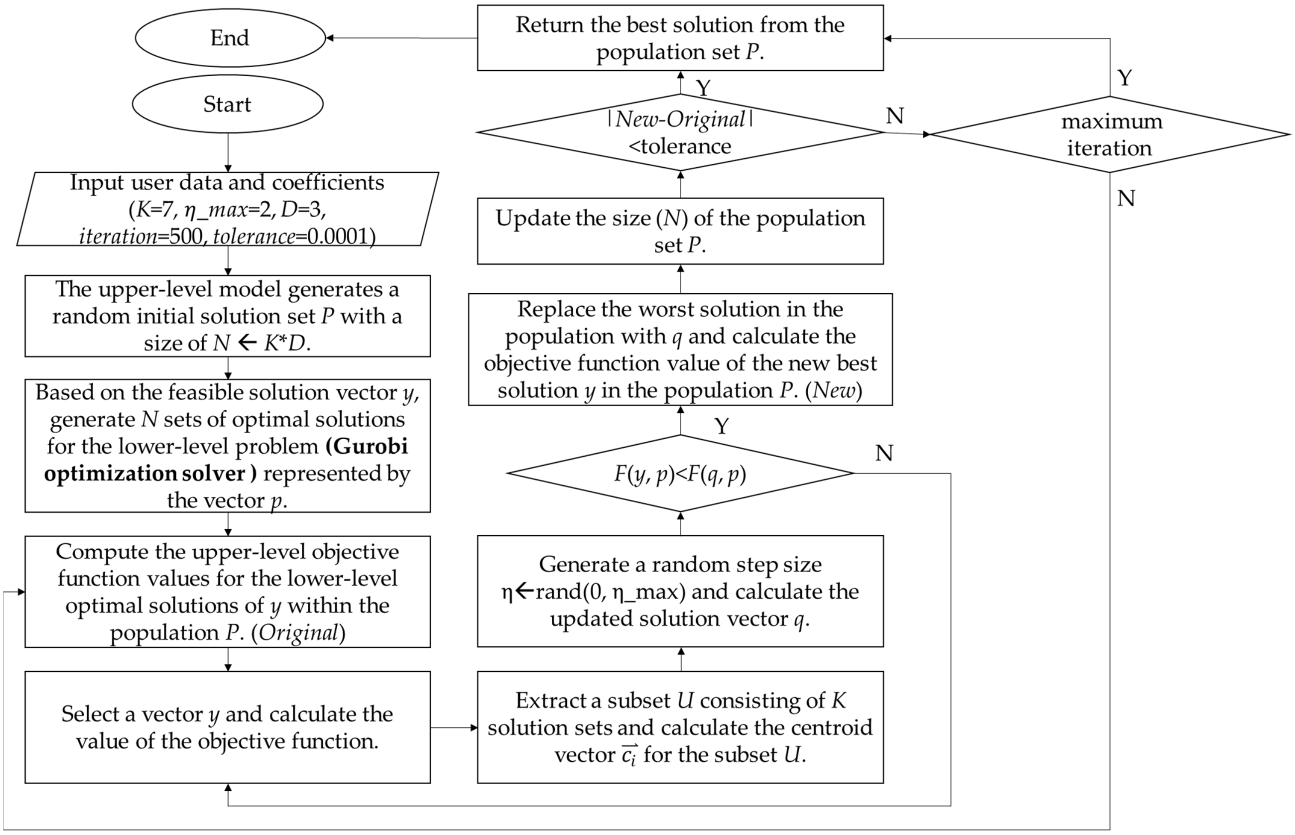


Figure 2. Solution steps flowchart for the hybrid algorithm in bi-level problem solving.

5. Numerical Results

In Taiwan, the regulations regarding renewable energy obligations for major electricity consumers have been put into effect; however, they are currently under intense discussion. One of the most contentious points among non-governmental organization (NGO) groups is the suggestion to raise the renewable energy consumption of large electricity consumers to 20%. This proposal shifts the emphasis from a proportional approach based on installed capacity to attaining a 20% share of electricity consumption as the primary implementation strategy, aiming to achieve the objective of transitioning to a net-zero emissions scenario. Furthermore, there is a debate about the requirement for major electricity consumers to install self-built solar power systems on their rooftops, which should not be replaced by certificates. NGO groups argue that obligated consumers should first meet a specific proportion of self-built solar power on their rooftops before they can offset their obligation by purchasing green energy certificates.

In this study, we utilize demand-side data from a particular RE100 company in Taiwan for the year 2020 as the validation reference. The company is pursuing the RE20 target, which serves as the foundational obligation, requiring them to achieve a 20% renewable energy consumption rate on an hourly basis. Concurrently, the government has set a target for this company to reach 40% renewable energy consumption throughout the entire year. Furthermore, businesses are increasingly prioritizing the integration of solar power and energy storage to meet the demand for self-built renewable energy and reduce reliance on certificates. Considering government subsidy policies, a collaborative strategy is formulated between the government and the company to fulfill these objectives. The results of key decision indicators for the bi-level programming model are presented in Table 2. It is important to note that these values are specific to the case study and can be influenced by changes in objective settings and parameter variations. However, in comparison to these decision indicators, the utilization and fluctuations of PV and energy storage capacities throughout the year are of greater significance and warrant our attention.

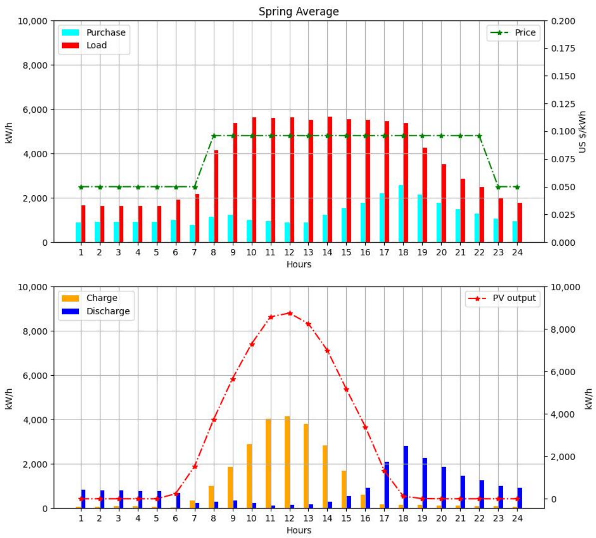
Table 2. Non-temporal resolution of decision outcomes in the upper- and lower-level models.

Model	Upper-Level		Lower-Level	
Objective	Total subsidy	US$ 4.1 million	Cost	US$ 6.7 million
Decision variables	PV subsidy	US$ 0.07/kWh	PV installation	22.9 MW
	Storage subsidy	US$ 0.56/kW	Storage installation	157.6 MW
	Electricity subsidy	US$ 0/kWh	PV generation	57.04%
			purchased electricity	23.72%
			Discharging	19.24%

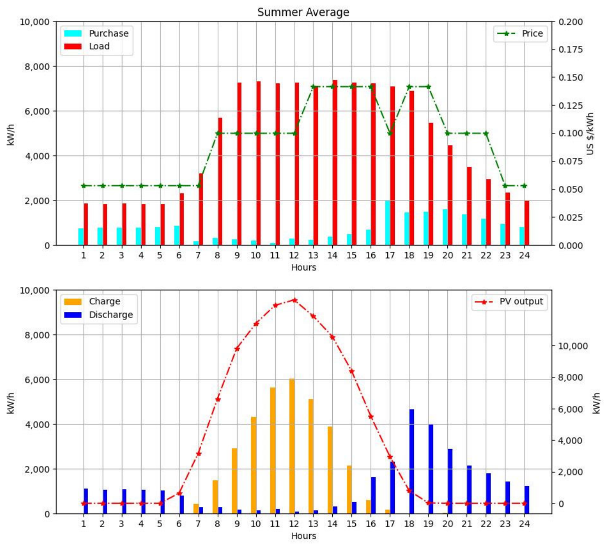
Table 2 illustrates the interconnectedness between the upper- and lower-level models, showcasing their respective solutions. The upper-level model offers greater subsidies for energy storage system installations, followed by subsidies for PV power generation. This approach incentivizes the lower-level model (users) to prioritize green energy usage to fulfill their energy needs. Moreover, the feed-in tariff (FIT) for solar power in Taiwan ranges from US $0.13 to $0.2 per kilowatt–hour (kWh), surpassing the average electricity price of approximately US $0.016 to $0.084 per kWh [19]. Although the FIT for rooftop solar power systems exceeding 20 kW drops below US $0.15/kWh, it still remains higher than the average electricity price by only US $0.036/kWh. Consequently, the government's projected subsidy for solar power amounts to US $0.07/kWh, which is relatively high, especially for large-scale installations. This is primarily due to the requirement of fulfilling 20% of the annual renewable energy share solely with solar power on an hourly basis, leading to increased costs compared to the average price. The emphasis on energy storage subsidies is mainly driven by the lower-level users' obligation to meet the RE20 hourly demand, particularly during nighttime, when energy can be sourced from storage.

The findings indicate that the businesses' obligation to generate 20% of their energy from renewable sources on an hourly basis allows them to meet 57.04% of their total annual energy demand. This accomplishment not only surpasses the government's target of 40% annual electricity generation from renewables but also highlights the crucial role of energy storage in maintaining power balance. With energy storage contributing to 19% of power through charge and discharge regulation, it becomes instrumental in sustaining power equilibrium. The power usage structure presented in Table 2 demonstrates the lower-level model's heavy reliance on PV power, accounting for a significant portion of electricity consumption. Although the RE20 requirement only represents 20% of the hourly renewable energy supply, the overall demand for renewable energy throughout the year surpasses this threshold. The provision of generous storage subsidies aids in minimizing unnecessary waste of excess renewable energy.

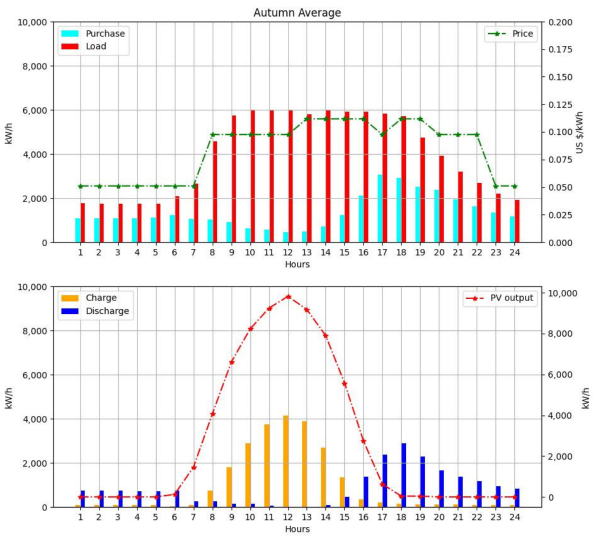
To facilitate the observation and interpretation of the model results, the optimization model in this study spans a one-year period, divided into hourly intervals. The resulting dataset is extensive, making it challenging to interpret due to its size. To enhance data interpretation, we present the results in a more manageable format by calculating the average values for each hour across four seasons: spring (March, April, May), summer (June, July, August), autumn (September, October, November), and winter (December, January, February). These results are visualized in Figure 3. By visualizing the data, we aim to facilitate their interpretation. Hence, we present the computational results of the optimization in the form of four seasonal result charts.



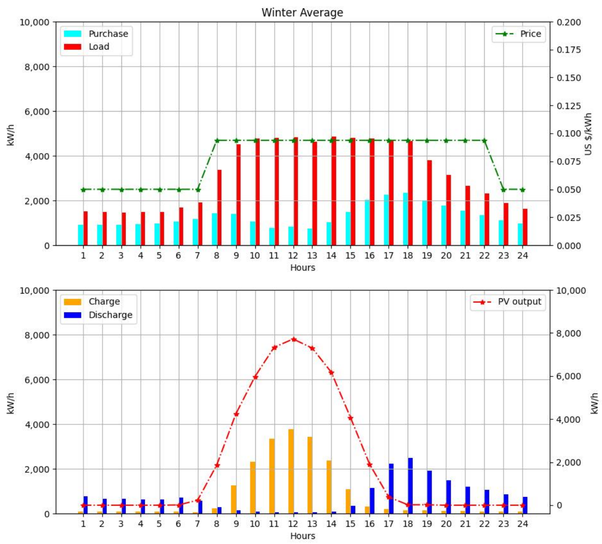
(**a**) Spring average data



(**b**) Summer average data



(**c**) Autumn average data



(**d**) Winter average data

Figure 3. The hourly data results of the lower-level model by season: (**a**) Spring average data; (**b**) Summer average data; (**c**) Autumn average data; (**d**) Winter average data.

Figure 3 is divided into two sections. The upper section of each season displays the relationship among load demand, electricity purchase quantity, and electricity purchase price. The horizontal axis represents the time periods, the left vertical axis represents the electricity quantity (in kilowatt–hour), and the right vertical axis represents the electricity price (in currency units). The light blue bars represent the electricity purchase quantity for each time period, the red bars represent the load demand for each time period, and they correspond to the left vertical axis. The green line represents the electricity purchase price for each time period, corresponding to the right vertical axis. The lower section of each season illustrates the relationship among energy storage charging quantity, energy storage discharging quantity, and solar energy generation. The horizontal axis represents the time periods, the left vertical axis represents the electricity quantity (in kilowatt–hour), and the right vertical axis represents the electricity quantity (in million kilowatt–hour). The dark blue bars represent the energy storage discharging quantity for each time period, the orange bars represent the energy storage charging quantity for each time period, and they correspond to the left vertical axis. The red line represents the solar energy output for each time period, corresponding to the right vertical axis.

Based on the data presented in Figure 3, it is evident that the daily insufficiency in solar energy output is offset by the discharging of the energy storage system and user electricity purchases. In situations where energy storage systems have higher charging and holding costs, the system tends to rely on electricity purchases to address smaller deficiencies. The system's operation aligns with the upper-level model's objective of achieving a green energy share exceeding 40% and the lower-level users' requirement of generating 20% renewable energy on an hourly basis. The main sources of supply in the system are PV system generation and energy storage system discharging. The majority of user load demand is met by PV output. However, if the PV generation capacity factor is inadequate, the model compensates for the shortfall through energy storage system discharging and electricity purchases. The energy storage system discharges when there is excess PV output beyond the user load requirements. This excess energy is stored and used during subsequent periods when there is no PV output available.

From Figure 3, it is evident that the peak user load for all four seasons occurs between 9:00 AM and 6:00 PM. To optimize electricity purchase costs, the optimal solution suggests buying electricity during periods of low demand and when the unit electricity price is lower than the charging cost of the energy storage system. With the exception of periods with insufficient solar energy such as sunrise and sunset, the PV system can meet the majority of the user load throughout the year. Excess solar energy during periods when the PV system meets the user load is stored in the energy storage system for use during periods without solar output. In summary, the optimal strategy involves using PV output to meet the majority of the user's high-demand load, charging the energy storage system during periods of excess PV output, and discharging the energy storage system along with purchasing electricity during periods without sufficient solar output.

In comparison to earlier research, although the combination of energy storage with solar PV power yields anticipated results, previous studies were limited in their ability to support businesses with precise energy storage planning from a strategic standpoint, particularly in relation to government subsidies. Moreover, these studies encountered challenges in determining the optimal timing and suitable capacity for energy storage charging and discharging. Furthermore, we present a case study involving hourly observations for a specific day, June 22, which is the day with the highest peak load of the year. This is depicted in Figure 4. To highlight the peak load analysis, we showcase the computational results of the optimization in the form of a single-day result chart.

As our study involves hourly analysis, we selected June 22, the day with the highest peak user load, for detailed examination. Figure 4 illustrates that during periods when the PV system is not generating electricity, specifically before 6:00 a.m. and after 7:00 p.m., the user's electricity demand is primarily fulfilled through a combination of energy storage system discharging and electricity purchases. Noticeable differences can be observed in the quantities of electricity purchased and discharged by the energy storage system during these periods. This disparity can be explained by the electricity price curve, as the lower-level objective aims to minimize costs. Furthermore, energy storage system discharging is contingent on the system being charged, which incurs relatively higher costs. Consequently, during periods with lower electricity prices, such as before 6:00 a.m. and after 8:00 p.m., the system opts to purchase electricity to compensate for the insufficient output from the PV system. Conversely, during the period of higher electricity prices, specifically from 6:00 p.m. to 7:00 p.m., the system primarily relies on energy storage system discharging to address the shortage in PV system output. Throughout the day, when the PV system generates electricity, it effectively meets a significant portion of the user's demand. Any surplus electricity beyond the user's needs is stored in the energy storage system to be utilized during periods without PV output.t

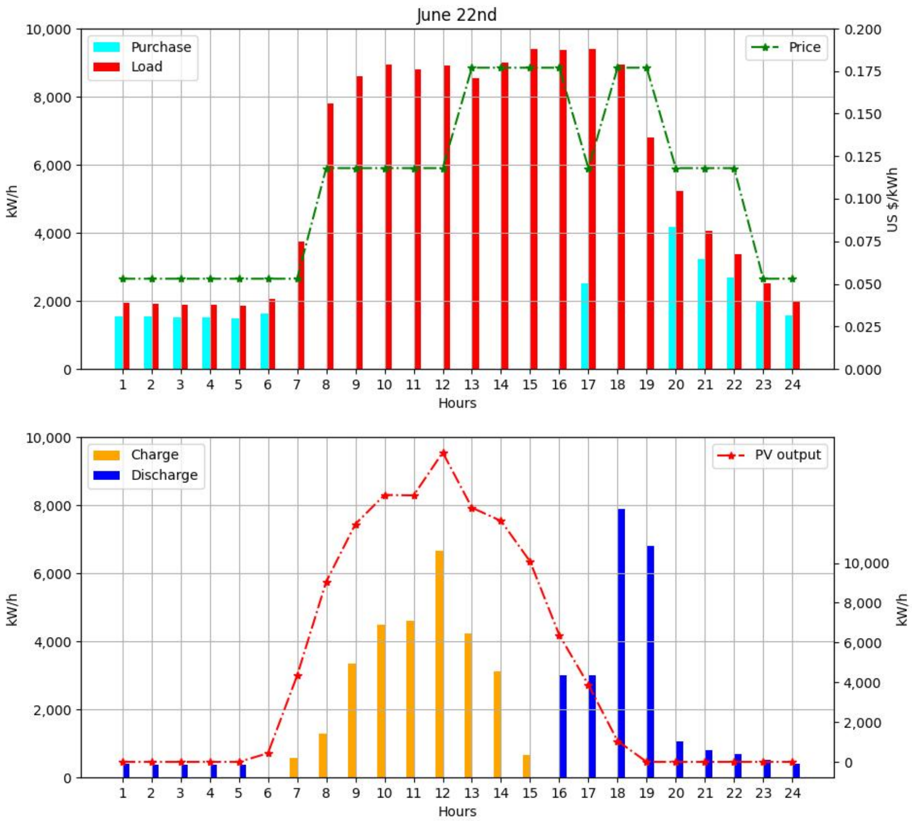


Figure 4. Hourly results of peak load day.

6. Conclusions and Future Work

In conclusion, the bi-level optimization model proposed in this study aims to effectively integrate the objectives of the government and users by utilizing PV and energy storage systems. It addresses the management of user energy consumption and explores system arrangement characteristics under government subsidy policies. To tackle the complexity of the bi-level model, a hybrid physics-inspired algorithm for bi-level programming is introduced for optimization. The model results indicate that the optimal solution for meeting user load demands involves primarily relying on PV output during peak load periods. When the PV system output nearly exceeds the user load, a small amount of electricity is purchased, while the excess electricity is utilized to charge the energy storage system. During periods of low demand, the model suggests purchasing electricity and utilizing energy storage system discharging to meet user load requirements. Analysis of the seasonal data charts reveals that user load is highest between 9:00 AM and 6:00 PM across all seasons, with the electricity purchase price for users positively correlated with the load. Consequently, the optimal solution recommends increasing electricity purchases during non-peak periods, as the unit charging cost of the energy storage system exceeds the unit cost of electricity purchases. The model also considers the holding cost of the energy storage system and avoids redundant charging. Taking these factors into account, the proposed optimization model offers a feasible and cost-effective solution for managing user energy consumption.

Based on the research findings, the following conclusions can be drawn:

1. The proposed bi-level optimization model in this study enables the effective formulation of different electricity strategies and management of user energy consumption based on their specific needs. It also considers government subsidy policies, making it practical and feasible.

2. The model also takes into account the reduction in carbon emissions and the promotion of green energy utilization, making it relevant to environmental protection issues and offering potential for further development.
3. This study analyzes seasonal data charts and proposes the optimal solution of increasing electricity purchases during non-peak periods to reduce the cost of the energy storage system.
4. The results demonstrate that utilizing PV output during peak load periods, along with a small amount of electricity purchasing and storing the excess energy in the storage system, achieves the optimal electricity plan.
5. During low-demand periods, the model suggests purchasing electricity and utilizing energy storage system discharging to meet user load demands, thus minimizing electricity costs.

In this study, we simplified the government-side decision variables to enhance the solvability of the bi-level model, with a primary focus on user-side planning. Future research can enhance the government-side decision variables and develop a comprehensive leader–follower game model. Furthermore, the current model only considers hourly considerations and self-built solar facilities on the user side, without incorporating the procurement of renewable energy from external sources. Subsequent studies can explore the purchase of solar or wind power from external sources, taking into account the location of power plants, to examine the influence of different generation patterns. Additionally, minute-based modelling can be considered to create a more intricate and refined model.

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