

Article

Optimization of the Coupling between Water and Energy Consumption in a Smart Integrated Photovoltaic Pumping Station System

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Abstract: Agricultural irrigation requires significant consumption of freshwater resources and energy. The integration of photovoltaic power generation into irrigation systems has been extensively investigated in order to save the cost of energy. However, current research often neglects the coupling relationship between photovoltaic power generation and irrigation schemes. This study presented a novel smart integrated photovoltaic pump station system to effectively address the issue associated with water and energy consumption in irrigation. An optimization model was proposed to synchronize the energy consumption of irrigation pump stations with photovoltaic power generation, accurately meeting the irrigation water demand while maximizing solar energy utilization. The optimization model incorporates power balance, grid-connected power, and total water demand as constraints while considering pump speed as the decision variable and aiming to minimize daily operational costs. Finally, a high-standard farmland was used as a case study to validate the efficacy of the optimization strategy through two photovoltaic grid-connected policies—one allowing for the sale of surplus power and the other prohibiting it. An improved dynamic programming method was employed to solve for optimal energy consumption schemes under different water demand conditions; the results were compared against traditional methods, revealing potential cost savings ranging from 6.2% to 30.5%. The optimization model and method propose a new operational concept for the irrigation system with photovoltaic generation, effectively utilizing the distinctive features of both irrigation and photovoltaics to optimize water and energy resources.

Keywords: photovoltaic irrigation; energy optimization; dynamic programming; integrated pumping station

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1. Introduction

Globally, agriculture is a significant consumer of freshwater resources, and the projected acceleration in global population growth highlights the imminent surge in food demand, which directly impacts agricultural water usage [1,2]. Moreover, escalating carbon dioxide emissions contribute to an upsurge in greenhouse gases and accelerate climate change. Humanity faces another grave challenge in the 21st century—global warming. Carbon emissions are intricately linked to human activities, as people extensively consume fossil fuels and electricity energy both in production and daily life, giving rise to numerous environmental predicaments [3–5]. Notably, agriculture irrigation not only requires substantial amounts of freshwater resources but also demands significant electrical energy consumption. Therefore, considering the scarcity of water and electricity resources, as well as the imperative to reduce carbon emissions, enhancing water efficiency and controlling energy consumption have emerged as pivotal concerns in irrigation practices [6].

Nowadays, the research on water-saving irrigation has predominantly focused on optimizing irrigation programs to minimize water consumption by developing optimization scheduling models that effectively integrate factors such as crop growth cycles and weather information [7–9]. By implementing well-designed irrigation plans, it is possible to achieve a harmonious balance between maximizing yield and enhancing water efficiency [10]. Despite the theoretical validation of these optimal irrigation schemes, real-time adjustment of output water volume based on optimization results remains a challenge for pumping stations due to inadequate hardware and software support, thereby hindering the implementation of aforementioned optimal irrigation strategies. The study of an integrated pumping station, which incorporates data detection and automatic control, presents a significant solution for addressing this issue. Furthermore, the implementation of advanced irrigation technologies, such as pipe irrigation and drip irrigation systems, can effectively address the issue of water consumption. It is important to note that these methods necessitate substantial initial investment costs [11,12].

Optimizing irrigation programs can reduce water consumption and indirectly lower electricity energy usage, but more significant reductions in energy consumption can be achieved through the direct optimization of the energy mix and its utilization methods [13]. Currently, with the advancements in new energy technologies, the application of photovoltaics (PVs) as a green renewable energy source for agricultural irrigation has garnered extensive attention [14,15]. Many studies have confirmed the superiority of photovoltaic irrigation [16,17]. Taousanidis et al., considering climate and economic conditions, demonstrated the advantages of photovoltaic irrigation using Life Cycle Cost (LCC) analysis [18]. Munarto et al. conducted a feasibility analysis on applying a photovoltaic system in rice irrigation [19]. The exploration of strategies for maximizing the rational and efficient utilization of photovoltaic energy warrants particular attention, especially in regions where government subsidies have been discontinued and excessive grid-connection has been restricted [20,21]. Furthermore, due to the intermittent nature of photovoltaic energy, traditional approaches primarily involve the utilization of energy storage methods (such as electricity or other conversion forms like water towers) in order to meet the demand of electricity load. This inevitably leads to an escalation in equipment costs [22,23].

In summary, although extensive research has been conducted on the application of irrigation and photovoltaic systems, there remains a lack of integration between the characteristics of photovoltaic power generation and the optimization of water and energy coupling based on irrigation water demand. By investigating the patterns of electricity usage in irrigation, we have observed that the temporal dynamics of irrigation electricity demand differ significantly from those of industrial electricity consumption [24]. Given that the overall requirement for irrigating water is fulfilled within the designated timeframe, it becomes feasible to flexibly transform and adjust electricity demands accordingly [25]. These findings serve as a foundation for optimizing water and energy consumption coupling. Expanding upon this conceptual framework, this study developed an integrated smart pump station equipped with photovoltaic power generation capabilities. This advanced system enables real-time and precise control of water volume, providing essential hardware and software support for optimizing irrigation operations. To maximize the utilization of photovoltaic energy, an optimization model was proposed that integrates the power consumption trajectory of the irrigation system with the power generation trajectory of photovoltaic energy. The optimization model proposed in this paper represents a typical high-dimensional nonlinear system, for which heuristic algorithms are commonly employed as the mainstream approach to problem-solving [26,27]. However, the presence of equality constraints and judgment constraints in this specific optimization model poses challenges for heuristic algorithms to efficiently handle such constraints, despite the potential use of penalty function methods to address the issue [28–30]. Therefore, considering these characteristics of the proposed optimization model, an improved dynamic programming algorithm was adopted in this study as an effective solution strategy specifically tailored for handling equality constraints.

According to the optimization results of the model, the system will automatically adjust the pump's output power based on fluctuations in photovoltaic power generation, thereby regulating irrigation load and achieving electricity load tracking aligned with photovoltaic power generation trajectory. This adaptive approach enables power load adjustment without requiring additional energy storage equipment, thus significantly enhancing photovoltaic power utilization efficiency. Smart pumping stations also play a crucial role in precisely meeting total irrigation water requirements. This methodology not only achieves substantial energy savings and emission reductions but also reduces farmers' water and electricity costs while augmenting their overall income.

The proposed devices, model, and method were implemented on a 200 ha high-standard farmland in Suzhou, China. The system considered two distinct photovoltaic policies and optimized calculations for varying daily irrigation water requirements, resulting in favorable outcomes. By utilizing the precise irrigation technology of the smart pumping station and integrating it with an optimized model for the water and energy based on photovoltaic power generation, cost savings ranging from 6.2% to 30.5% were achieved in comparison to conventional photovoltaic irrigation methods. The optimization method presents a novel operational concept for photovoltaic-equipped pump stations, enabling the maximization of photovoltaic energy utilization without the need for additional energy storage devices. It can also be extended to the industrial field, where the rational arrangement of various processes enables the adjustment of daily electricity consumption trajectory. This alignment aims to closely align each state's electricity consumption trajectory with that of photovoltaic power generation, maximizing the utilization of solar energy and minimizing reliance on grid-supplied electricity, thereby reducing operational costs. However, achieving this requires a comprehensive integration of power load management, production supervision, task allocation, and scheduling. Consequently, this intricate yet captivating inquiry warrants further exploration in future investigations.

2. Materials and Methods

2.1. Description of the System

Generally, the irrigation system comprises three components: house, pump and electrical equipment. The conventional pump house is constructed using bricks, which results in longer construction periods and larger areas, making it inconvenient for relocation. Moreover, its control function is limited to basic start-stop operations. To address these problems, this study proposed an integrated pump station system equipped with photovoltaic that incorporates standardized and modular design principles, enabling seamless installation along with comprehensive control and acquisition functionalities. The concept of the integrated photovoltaic irrigation system is depicted in Figure 1. The core of the system comprises the pump system, the power supply system (including grid and photovoltaic power generation), the detection system (data acquisition and feedback), and the control system (system optimization and automatic control of the pump station). These components are seamlessly integrated within a mobile pump house constructed from metal or environmentally friendly materials. Through this integrated smart pumping station, precise irrigation and efficient energy distribution can be achieved. From Figure 1, the irrigation electricity was supplied through a combination of the distribution network and photovoltaic system, where P_{gid} represents bidirectional grid energy flow, P_{pv} denotes photovoltaic power, and P_m signifies the power demand for irrigation at the pumping station.

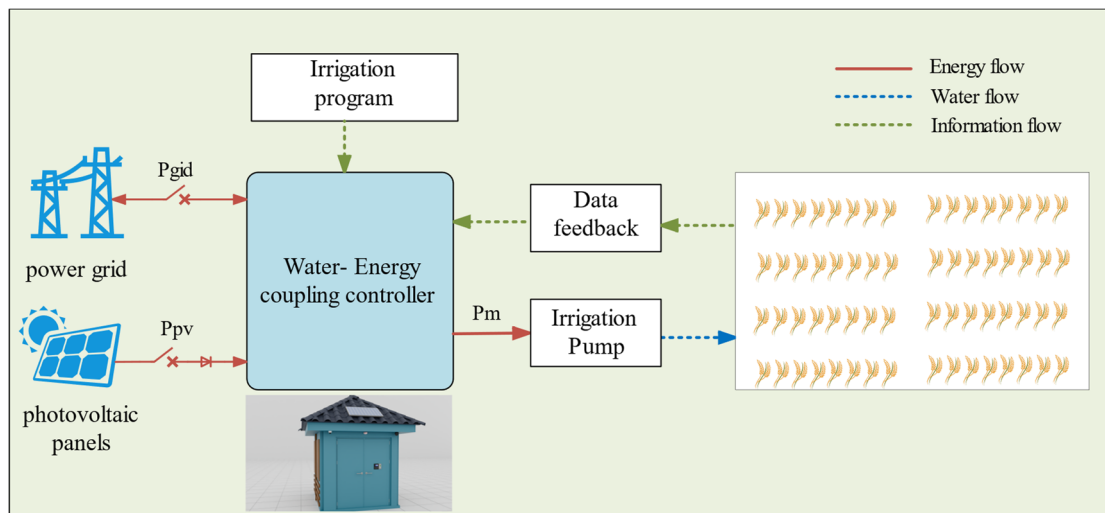


Figure 1. The schematic of photovoltaic irrigation system.

Based on the smart integrated photovoltaic irrigation system, a strategy for energy optimization was proposed that integrates the energy consumption track of irrigation systems with the power generation track of photovoltaic energy. This strategy dynamically adjusts the pump power of each stage according to changes in photovoltaic power generation while meeting overall water demand, changes the power track of pumping station operation, and realizes load transfer so that the change in pumping station power is closest to the photovoltaic power output. This maximizes the use of photovoltaic energy and effectively reduces operating costs. Figure 2 illustrates the conceptual diagram for energy optimization.

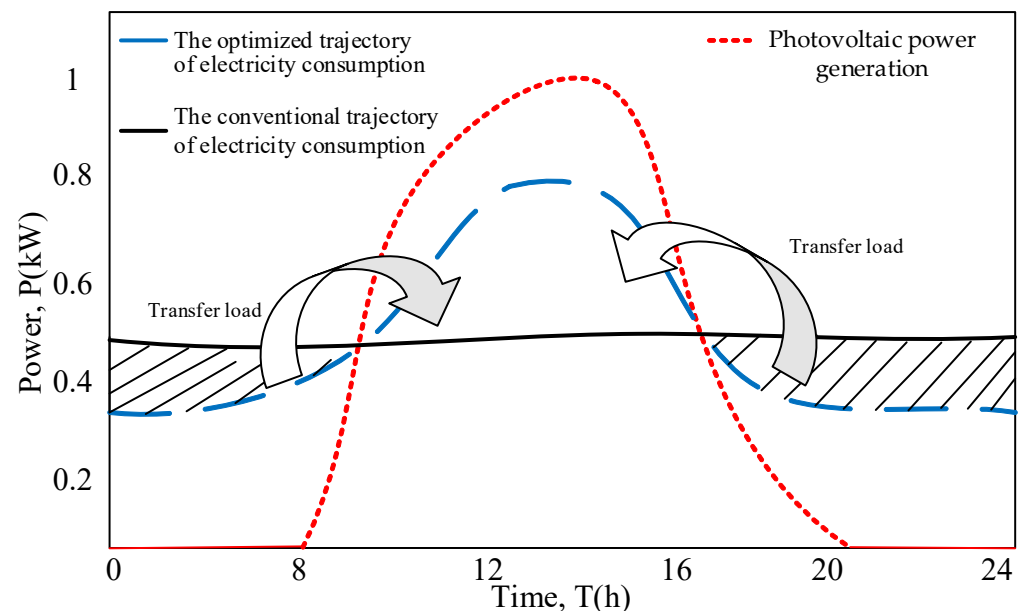


Figure 2. The conceptual diagram for energy optimization.

2.2. Optimization Model

2.2.1. Objective Function

According to the principle of coupled optimization for water and electricity energy supply and demand, an optimization model was developed with the objective of minimizing daily operational costs for irrigation pumping stations, as depicted in Equation (1). The

model discretizes each day into 24 stages, with pump speed considered as the decision variable while ensuring a balance between water and electricity energy.

P_{gid} represents the power exchanged between the pumping station system and the electric grid during time i . The coefficient σ denotes the direction of power flow. The value of σ being 0 indicates that the photovoltaic power fails to meet the power requirements of the pump, requiring the system to obtain power from the grid. On the other hand, a value of 1 indicates surplus energy generated by photovoltaic systems when the power output exceeds the actual demand of the pump, allowing for its sale back to the grid. In case there is a prohibition on photovoltaic grid connection, as shown in Equation (2), σ will always be zero. In addition, the electrical energy required for irrigation at the pump station is denoted as $P_m(n_i)$, while n represents pump speed. It should be noted that the power of the pump can be adjusted by altering the motor speed through a frequency converter. Equation (3) illustrates their functional relationship

$$F = \min \sum_{i=1}^{SN} \{ \sigma \cdot P_{gid}(n_i) \cdot C_i^{sell} + (1 - \sigma) \cdot P_{gid}(n_i) \cdot C_i^{buy} \} \cdot \Delta T_i \quad (1)$$

$$P_{gid}(n_i) = P_m(n_i) - P_{pv,i} \quad (2)$$

$$P_m(n_i) = \frac{\rho g Q_i(n_i) H_i}{\eta_{z,i}(n_i) \eta_{mot} \eta_{int} \eta_f} \quad (3)$$

$$\sigma = \begin{cases} 1 & P_{gid} \leq 0 \\ 0 & P_{gid} > 0 \end{cases} \quad (4)$$

where

F : daily operating cost (¥)

SN : the number of stages in a day

n_i : the motor speed in stage i (r/min)

ρ : density of water (1000 kg m⁻³)

g : standard gravity (9.8 m s⁻²)

$Q_i(n_i)$: the pump flow when speed is n_i in stage i (m³/h)

H_i : pumping head in stage i (m)

η_{mot} , η_{int} , η_f : motor drive efficiency ($\eta_{mot} * \eta_{int} * \eta_f$) = 90.24%. η_{mot} represents the motor's efficiency, η_{int} denotes the efficiency of the drive component, and η_f signifies the efficiency of the inverter.

$\eta_{z,i}(n_i)$: the pump efficiency when speed is n_i in stage i (%)

$P_{pv,i}$: PV power in stage i (kW)

C_i^{buy} : the price of the grid (¥/kW·h). When purchasing electricity from the grid, C_i^{buy} is 0.509 ¥/kW·h according to the agricultural guiding price, and C_i^{sell} is 0.391 ¥/kW·h when selling electricity to the grid in Jiangsu Province, China

ΔT_i : stage time length (h); $\Delta T_i = 24 \text{ h}/SN$

2.2.2. Constraints

- Power balance constraint

$$P_{gid,i} = P_m(n_i) - P_{pv,i} \quad (5)$$

$$0 \leq P_{gid,i} \leq P_{bmax} \quad (6)$$

$$0 \leq -P_{gid,i} \leq P_{smax} \quad (7)$$

The maximum exchange power of the pumping station system and grid, represented by P_{bmax} and P_{smax} , respectively, should be determined based on the capacity of the trans-

former at their connection point and specific policies. When setting P_{bmax} to correspond with the peak photovoltaic power, it enables full energy exportation to the grid. Conversely, setting P_{smax} to 0 prohibits any sale of photovoltaic power.

- Water demand constraint

$$\sum_{i=1}^{SN} Q_i(n_i)\Delta T_i = W_e \quad (8)$$

where W_e is the daily irrigation water demand (m^3/d).

- Speed constraint

$$n_{min} \leq n_i \leq n_{max} \quad (9)$$

$$n_i \in \mathbb{Z} \quad (10)$$

where n_{min} and n_{max} represent the minimum and maximum admissible values of pump speed, respectively. Insufficient pump speed can significantly impair efficiency, while excessively high speeds may exceed the rated power threshold, potentially resulting in pump damage. Therefore, considering both pump power and efficiency, a speed constraint is implemented as a performance limitation for the pump. Additionally, to align with practical frequency converter characteristics, integer values are preferred for setting the speed.

2.3. Solving Methods

The optimization model is a multi-dimensional and multi-stage nonlinear model with both equality and judgment constraints, which is evident from its complexity. The heuristic algorithm is commonly employed for addressing nonlinear optimization problems; however, effectively handling equality constraints and judgment constraints within the model can present challenges for heuristic algorithms. In contrast, dynamic programming (DP), which can break up a problem into a series of overlapping sub-problems, builds up solutions to larger and larger sub-problems [31], utilizing DP as the primary algorithm appears to be a rational choice for tackling these issues.

The recursive equation and the state transformation function (Equations (11) and (12)) can be derived based on the objective function and the coupling constraint condition (Equations (1) and (8)), where $f(n)$ is the objective function Equation (1) and λ is the state variable related to the coupling constraint condition Equation (8) which plays a crucial role in the principle of DP algorithm. We are aware that the presence of continuous variables can pose challenges in the process of solving dynamic programming problems. However, for decision variables such as speed, considering practical applications, it is feasible to discretize them into a sequence of integer values. Therefore, the state variable λ_i and the decision variable motor speed n_i are discretized within their feasible region, where λ_i takes values from 0 to W_e and n_i ranges from n_{min} to n_{max} . The smaller the discrete step size, the higher the level of calculation accuracy that can be achieved; however, this may result in increased computational time, necessitating a comprehensive decision-making process. An additional issue arises when attempting to solve the recurrence equation, as $\lambda_i - Q_i(n_i)\Delta T_i$ may not necessarily be present in $g_{i-1}(\lambda_{i-1})$ from the preceding state. To address this issue, this paper proposed targeted modifications to the iterative process of DP, as illustrated in Figure 3. The algorithm employs a table to store the values of each $g_i(\lambda_i)$ and utilizes a nearest search approach for efficient retrieval, ensuring that $\lambda_i - Q_i(n_i)\Delta T_i$ consistently identifies the closest value and minimizes algorithmic errors [32].

$$g_i(\lambda_i) = \min_{0 \leq n_i \leq \xi_i} \{f(n_i) + g_{i-1}(\lambda_{i-1})\} \quad (11)$$

$$\lambda_{i-1} = \lambda_i - Q_i(n_i)\Delta T_i \quad i = 2, 3, \dots, SN - 1 \quad (12)$$

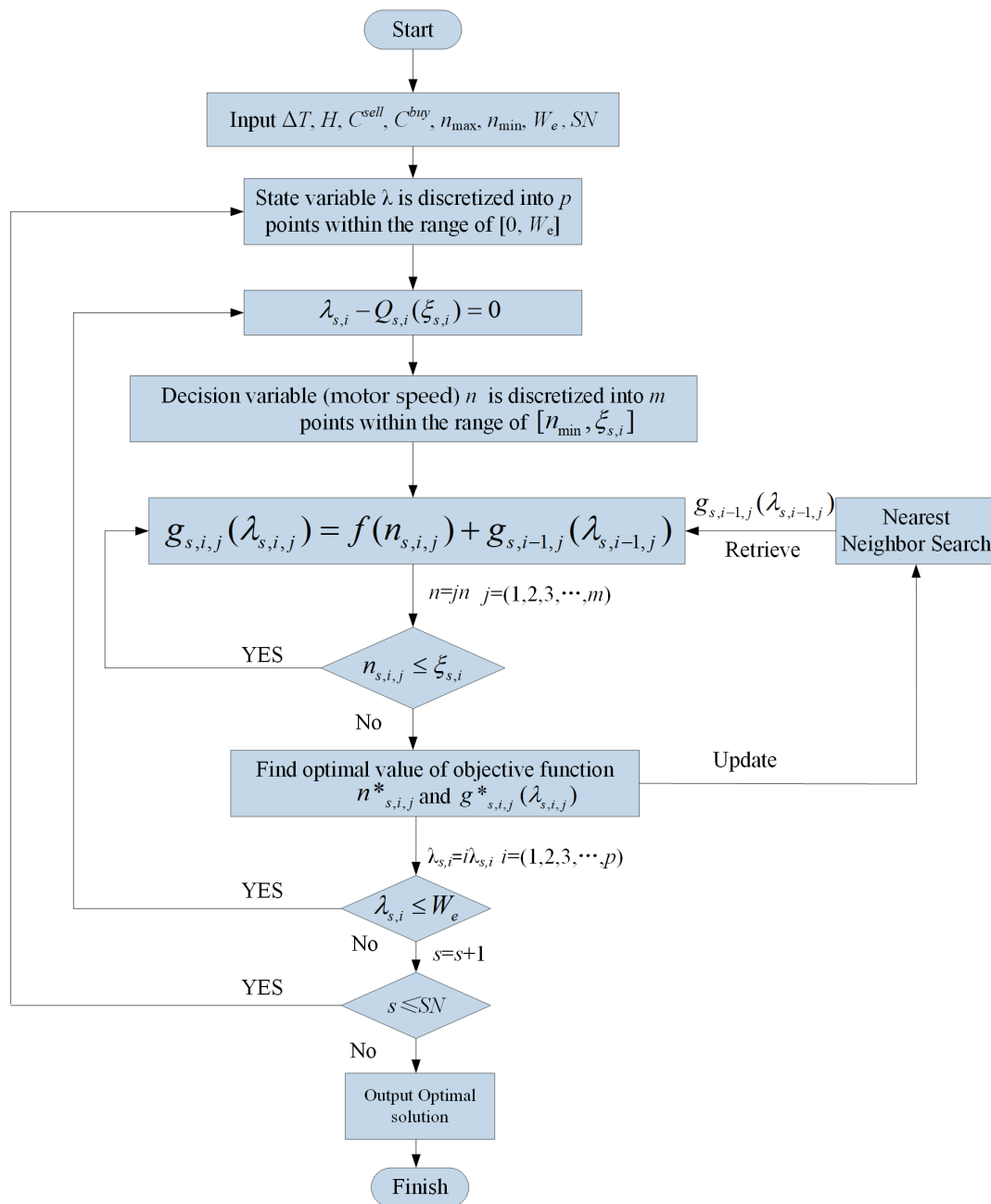


Figure 3. Dynamic programming algorithm flow, where s is the stage variable, the state variables λ of each stage are discretized by p points and denoted as $\lambda_{s,i}$. Each determined $\lambda_{s,i}$ yields a range of decision variables $[n_{min}, \xi_{s,i}]$, within which the decision variable n is discretized into m points denoted as $n_{s,i,j}$. and $n_{s,i,j}^*$ is the optimal value for the current state.

3. Results

The proposed photovoltaic irrigation system was implemented in a high-standard farmland situated in Suzhou, Jiangsu, China. The water pump model, 250HW-8C, has a rated head of 12 m, rated flow of 660 m³/h, and rated speed of 1450 r/min. The motor power driven by the frequency converter is 30 kW. Based on the manufacturer-provided pump parameters, as shown in Figure A1, the water pump performance equations presented in the Equations (13) and (14) are derived using the similarity theorem. Due to the significant volume of the watercourse and minimal variation in the daily average head, it can be assumed as constant. Assuming a pumping head of 10 m, the motor speed is maintained

within the range of 1100 r/min to 1450 r/min, taking into consideration the overall efficiency and usage patterns of the pump.

$$H(n_i) = -2.03e^{-5}Q_i^2 + 9.99e^{-7}n_iQ_i + 9.579e^{-6}n_i^2 \quad (13)$$

$$\eta(n_i) = -661.856\left(\frac{Q_i}{n_i}\right)^3 + 191.096\left(\frac{Q_i}{n_i}\right)^2 + 232.29\frac{Q_i}{n_i} - 0.2615 \quad (14)$$

The effectiveness of the optimization model and dynamic programming algorithm were validated by employing different typical daily irrigation water volumes (6000 m³, 7000 m³, and 8000 m³). Figure 4 illustrates the typical daily distribution of photovoltaic power in this region with a peak output power of 22 kWp (kilowatt-peak). Simultaneously, Figure 4 also depicts the power curve under traditional timing operation. As depicted in the figure, conventional irrigation methods generally neglect the potential of photovoltaic power generation and solely focus on meeting water demand requirements. Consequently, the implementation of diverse photovoltaic policies does not exert influence on the operational dynamics of irrigation systems.

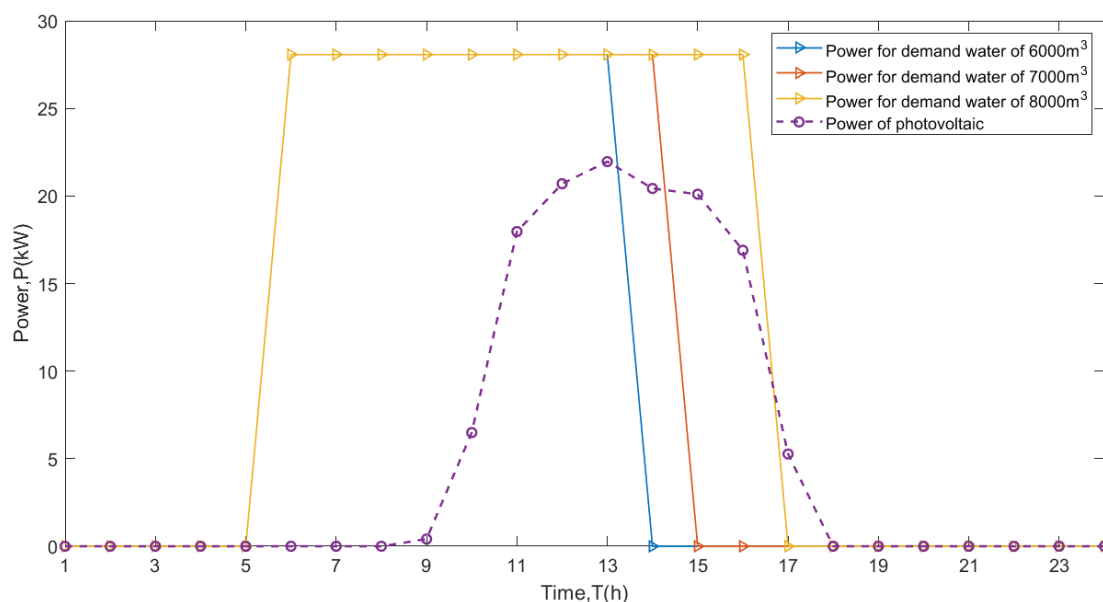


Figure 4. Power trajectory of the pump in conventional operation.

According to the proposed optimization model and algorithm, Figures 5 and 6 depict the power curve of the pump during optimized operation under different photovoltaic grid-connected policies. In Figure 5, we considered scenarios where surplus photovoltaic energy can be fed into the grid for electricity sales, while in Figure 6, it demonstrated situations where such connection of excess photovoltaic energy was prohibited by the grid. As depicted in the figures, the pump's power can self-adjust along with the photovoltaic power, ensuring that total water quantity meets demand and enabling the translation of electricity load. This ensures the maximum utilization of photovoltaic energy while saving energy and reducing irrigation costs.

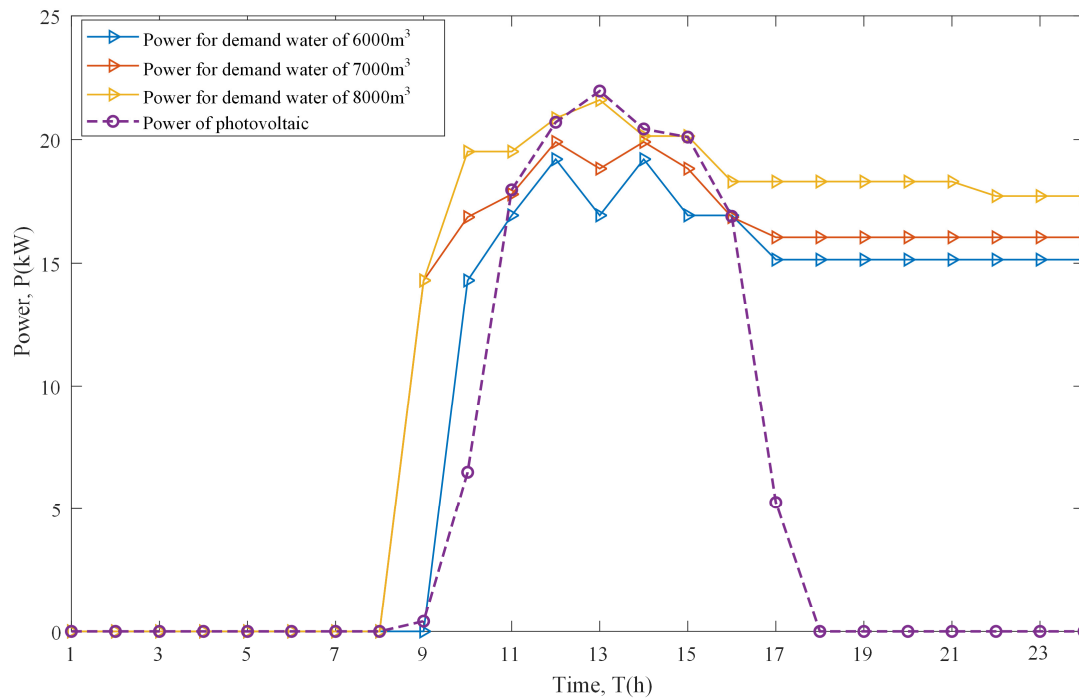


Figure 5. Power trajectory of the pump in optimized operation when surplus photovoltaic power is permitted for sale.

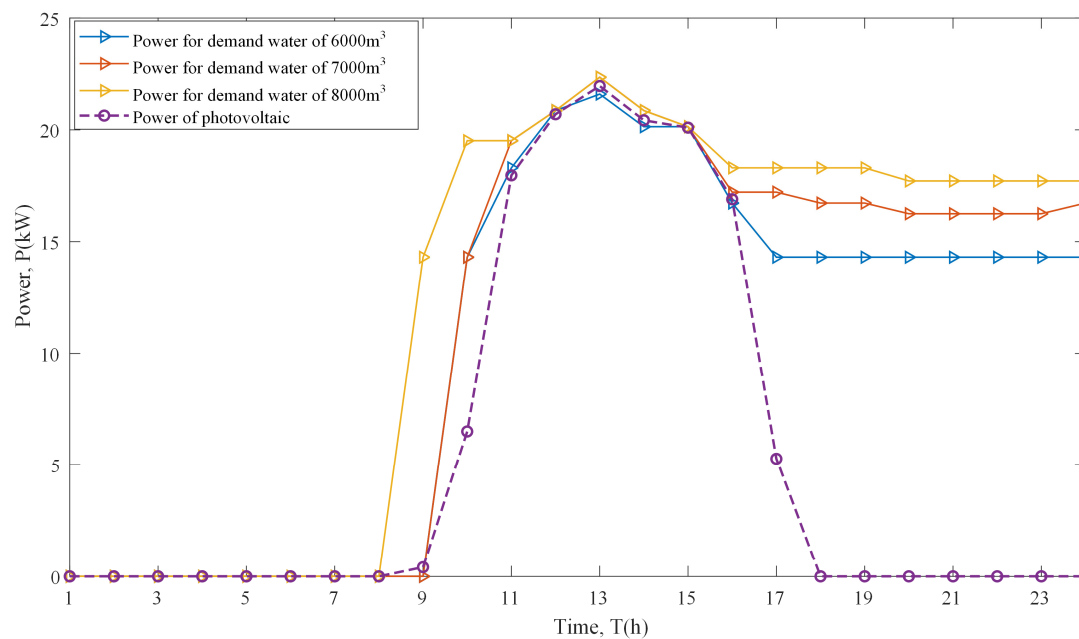


Figure 6. Power trajectory of the pump in optimized operation when surplus photovoltaic power is prohibited from sale.

The specific operational conditions of the system at each stage under different photovoltaic strategies, including pump speed, power, and water volume, are presented in Tables 1 and 2. Table 3 presents a comprehensive overview of the costs and water supply associated with pumping station operations across different modes. It can be seen from Tables 1 and 2 that by optimizing and adjusting decision variables in real time, pump speed changes accordingly, thereby altering the power and flow of the pump. Due to the wide range of adjustment provided by the inverter, the flow regulation of the pump station can be more precise. Additionally, the integration of an automatic closed-loop

control mechanism in the pump system further enhances water control precision at the pump station, enabling it to meet users' specific water requirements accurately. On the contrary, as observed in Table 3, traditional methods fail to meet water demand due to insufficient or excessive water supply, resulting in the wastage of precious resources. For example, for Table 3, the optimized water amounts are recorded as 5996 m³, 7001 m³, and 7999 m³, respectively, while traditional methods remain at 5946 m³, 6690 m³, and 8176 m³, respectively. Meanwhile, Table 3 demonstrates that optimized operations can result in cost savings ranging from 6.2% to 30.5%. Therefore, these optimized operations significantly improve the accuracy of irrigation water quantity while minimizing wastage through improved synergy between water and electricity energy.

Table 1. A daily operation optimization scheme when surplus photovoltaic power is permitted for sale.

Time	Water Demands								
	6000 m ³			7000 m ³			8000 m ³		
	Pump Speed (r/min)	Pump Power (kW)	Water Volume (m ³)	Pump Speed (r/min)	Pump Power (kW)	Water Volume (m ³)	Pump Speed (r/min)	Pump Power (kW)	Water Volume (m ³)
1–8	-	-	-	-	-	-	-	-	-
9	-	-	-	1102	14.30	312.01	1102	14.30	312.01
10	1102	14.30	312.01	1182	16.86	438.35	1254	19.51	531.22
11	1184	16.93	441.12	1208	17.79	473.41	1254	19.51	531.22
12	1246	19.21	521.49	1264	19.90	543.22	1288	20.86	571.32
13	1184	16.93	441.12	1236	18.83	509.15	1306	21.60	591.83
14	1246	19.21	521.49	1264	19.90	543.22	1270	20.14	550.33
15	1184	16.93	441.12	1136	18.83	509.15	1270	20.14	550.33
16	1184	16.93	441.12	1182	16.86	438.35	1222	18.30	491.51
17	1130	15.15	360.51	1158	16.05	403.95	1222	18.30	491.51
18	1130	15.15	360.51	1158	16.05	403.95	1222	18.30	491.51
19	1130	15.15	360.51	1158	16.05	403.95	1222	18.30	491.51
20	1130	15.15	360.51	1158	16.05	403.95	1222	18.30	491.51
21	1130	15.15	360.51	1158	16.05	403.95	1222	18.30	491.51
22	1130	15.15	360.51	1158	16.05	403.95	1206	17.72	470.78
23	1130	15.15	360.51	1158	16.05	403.95	1206	17.72	470.78
24	1130	15.15	360.51	1158	16.05	403.95	1206	17.72	470.78
Subtotal			6003.6			6998.5			7999.7

Table 2. A daily operation optimization scheme when surplus photovoltaic power is prohibited from sale.

Time	Water Demands								
	6000 m ³			7000 m ³			8000 m ³		
	Pump Speed (r/min)	Pump Power (kW)	Water Volume (m ³)	Pump Speed (r/min)	Pump Power (kW)	Water Volume (m ³)	Pump Speed (r/min)	Pump Power (kW)	Water Volume (m ³)
1–8	-	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	1102	14.30	312.01
10	1102	14.30	312.01	1102	14.30	312.01	1254	19.51	531.22
11	1222	18.30	491.51	1254	19.51	531.22	1254	19.51	531.22
12	1288	20.86	571.32	1288	20.86	571.32	1288	20.86	571.32
13	1306	21.60	591.83	1324	22.35	611.91	1324	22.35	611.91
14	1270	20.14	550.33	1288	20.86	571.32	1288	20.86	571.32
15	1270	20.14	550.33	1270	20.14	550.33	1270	20.14	550.33
16	1178	16.73	432.77	1192	17.21	452.08	1222	18.30	491.51

Table 2. Cont.

Time	Water Demands								
	6000 m ³			7000 m ³			8000 m ³		
	Pump Speed (r/min)	Pump Power (kW)	Water Volume (m ³)	Pump Speed (r/min)	Pump Power (kW)	Water Volume (m ³)	Pump Speed (r/min)	Pump Power (kW)	Water Volume (m ³)
17	1102	14.30	312.01	1192	17.21	452.08	1222	18.30	491.51
18	1102	14.30	312.01	1178	16.73	432.77	1222	18.30	491.51
19	1102	14.30	312.01	1178	16.73	432.77	1222	18.30	491.51
20	1102	14.30	312.01	1164	16.25	412.76	1206	17.72	470.78
21	1102	14.30	312.01	1164	16.25	412.76	1206	17.72	470.78
22	1102	14.30	312.01	1164	16.25	412.76	1206	17.72	470.78
23	1102	14.30	312.01	1164	16.25	412.76	1206	17.72	470.78
24	1102	14.30	312.01	1178	16.73	432.77	1206	17.72	470.78
Subtotal			5996.2			7001.6			7999.3

Table 3. The amount of water and the cost of the demand under different operating modes.

Demand Water (m ³)	Cost of Conventional Operation Mode			Cost of Optimized Operation Mode			Cost Saving	
	Mode 1 (¥)	Mode 2 (¥)	Irrigation Water (m ³)	Mode 1 (¥)	Mode 2 (¥)	Irrigation Water (m ³)	Mode 1 (%)	Mode 2 (%)
6000	55.43	79.94	5946.7	49.76	55.56	5996.2	10.2	30.5
7000	67.31	83.84	6690	63.15	64.83	7001.6	6.2	22.7
8000	91.52	93.58	8176	77.10	77.18	7999.3	15.8	17.5

Note: Mode 1 is the mode of the surplus photovoltaic power permitted for sale and mode 2 is the mode of the surplus photovoltaic power prohibited from sale.

4. Discussion

Based on the analysis presented in Table 3, it is evident that the highest cost savings are achieved when water consumption reaches 8000 m³, under the condition of allowing surplus photovoltaic power sales. In this model, both the grid and photovoltaic system engage in trade, but users can only sell photovoltaic power at a lower price compared to purchasing electricity from the grid. Therefore, optimizing operation primarily relies on guiding users towards rational electricity purchases and sales. It should be noted that during periods of high-power demand, such as when water demand reaches 8000 m³, any irrational power transactions will significantly escalate electricity costs and consequently amplify the impact of operational optimization.

When the sale of surplus photovoltaic power is prohibited, the benefits of optimized operation become more pronounced. Among these benefits, the highest proportion of cost savings occurs when the water demand is 6000 m³. This can be attributed to the relatively low water demand during this period, resulting in a smaller overall power demand and providing greater opportunities for operational optimization. As depicted in Figure 6, after implementing optimized operation strategies, the pump's power curves closely align with that of photovoltaic power generation. This not only reduces reliance on grid power purchases but also minimizes the waste associated with underutilized photovoltaic power generation. Consequently, irrigation electricity costs are significantly reduced.

It can be seen from Table 3 that different photovoltaic policies have a great impact on the optimization results, and more benefits are obtained when excess photovoltaic energy is prohibited from being connected to the grid. Of course, different photovoltaic cell capacities also have a certain impact on the results. On the basis of disregarding the initial investment cost, the influences of different capacities on the optimization model are discussed in Figure 7.

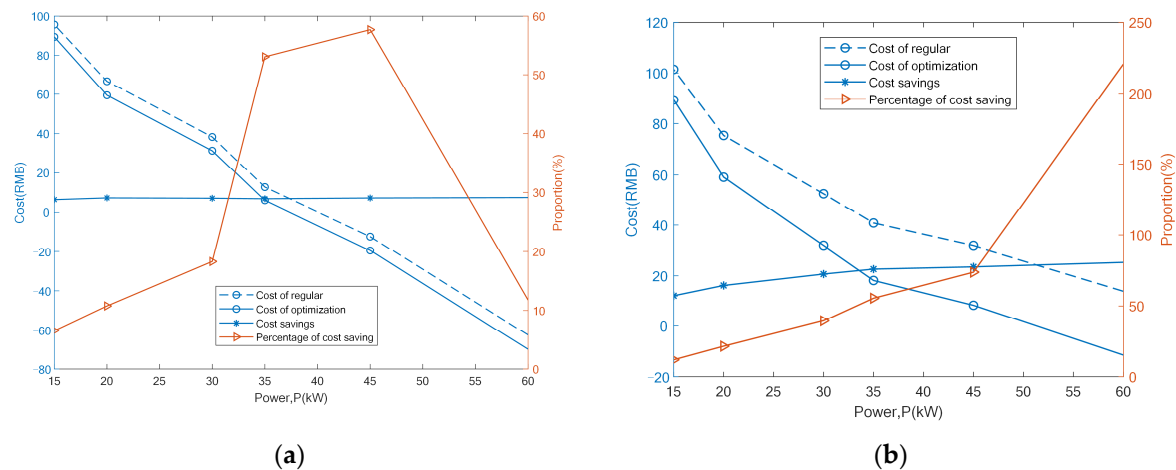


Figure 7. Comparison of optimization results of different photovoltaic capacities. (a) Surplus photovoltaic power is permitted for sale; (b) surplus photovoltaic power is prohibited from sale.

The aforementioned strategy was predicated on the established photovoltaic capacity. From Figure 7, an analysis will be conducted to ascertain its influence on the optimization method by fixing the water demand at 8000 m³ and adjusting the photovoltaic capacity parameter within a range of 15 to 60 kWp. The mode “surplus photovoltaic power is permitted for sale” is illustrated in Figure 7a. Due to motor power limitations, excessive photovoltaic energy cannot be fully utilized by the pump, resulting in a limited increase in benefits from optimizing the motor power trajectory with increasing photovoltaic capacity. However, as photovoltaic capacity increases, the advantages of electricity sales gradually escalate. Nevertheless, it is essential to consider the initial investment cost during actual operational processes. As depicted in Figure 7b, with an increase in photovoltaic capacity, the optimization results for the “Surplus photovoltaic power is prohibited from sale” mode improve. This is because, during this mode, the excess photovoltaic energy cannot be sold and a larger capacity leads to more surplus energy. The optimization model can effectively minimize this surplus, thereby enhancing income generation. However, the excessive photovoltaic energy will be wasted, resulting in low returns and leading to reduced cost efficiency. Hence, it becomes imperative to consider the alignment between motor power and photovoltaic capacity within this model. These issues can be addressed by developing corresponding optimization models in subsequent research.

5. Conclusions

The paper proposed an irrigation electricity energy utilization strategy for photovoltaic power generation from the perspective of the coupling relationship between photovoltaic power generation and irrigation schemes, aiming to address the issue of irrigation water and energy consumption. To achieve this goal, an integrated smart pump station with photovoltaic power generation was designed. The proposed optimization model and method can provide guidance for the frequency converter to adjust the operational power of the pump station in response to fluctuations in photovoltaic power generation. This method maximizes the rational utilization of photovoltaic energy without requiring additional energy storage equipment. The developed device, model, and algorithm were applied to a real case study, providing conclusive evidence that the proposed optimization method effectively enhances the utilization efficiency of photovoltaic energy in various scenarios involving photovoltaic power generation. It also reduces costs for agricultural producers while meeting irrigation water requirements. Therefore, the model and methodology presented in this study offer a novel approach to integrating renewable energy sources into agricultural practices, thereby facilitating the promotion of energy conservation and emission reduction in agriculture and fostering sustainable development. In future research endeavors, building upon the findings of this study, our focus will be on optimizing the

coupling between water and energy at a larger scale, encompassing aspects such as energy allocation and scheduling among different farms, carbon trading mechanisms, etc.

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Appendix A

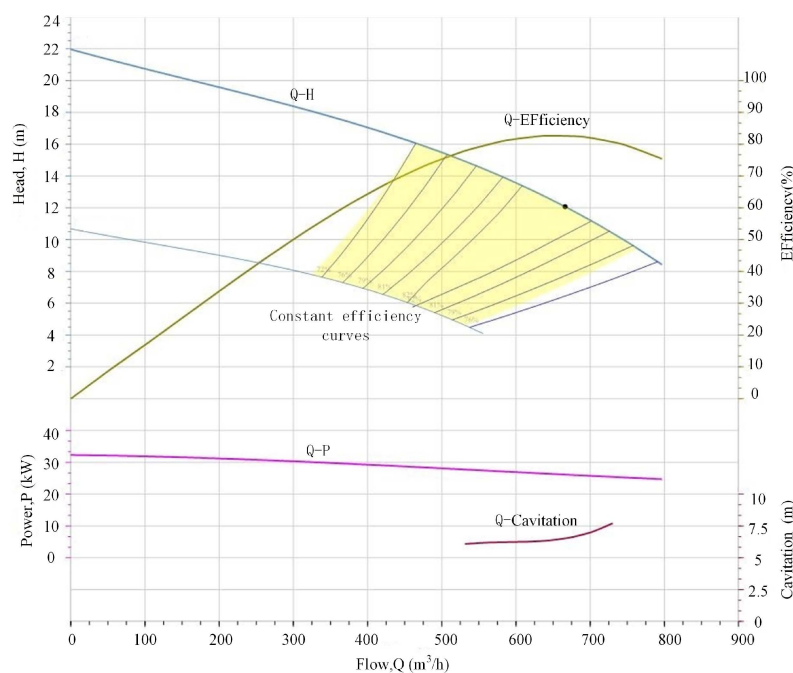


Figure A1. Basic characteristic curve of pump.

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