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Real-Time Energy Management With Demand Response in a PV-Battery Integrated Urban Aquaponics Farm

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ABSTRACT

Urban aquaponics farms, which combining recirculating aquaculture systems with hydroponics, are an innovative and eco-friendly way to meet the animal protein needs of urban populations with limited agricultural land and water resources. Aquaponics farms spend a large percentage of their total operating costs on electricity due to the wide variety of electrical equipment and a single energy supply method. This study proposes a demand response-based method for joint dispatch of greenhouse aquaponics PV output and load that can optimize the unit operation scheme and the battery storage charging/discharging activities to reduce operating costs and maximize the consumption of renewable energy. The case study demonstrates that the proposed method reduces the overall electricity consumption of the farm and improves sustainability and economic efficiency. The proposed approach promotes the sustainable growth of urban aquaponics farms.

Keywords: Urban aquaponics farms, renewable energy, demand response, energy management

NONMENCLATURE

Abbreviations	
PV	Photovoltaic
DR	Demand Response
Symbols	
I,i	Set and index of appliances
Ω,t	Set and index of time
J,j	Set and index of trigger elements
$P_{PV,t}$	The power generated by the PV modules
P*,G*	Maximum power and global irradiance at standard test conditions
G_t	The global irradiance
SF,TF	Spectral coefficients and thermal factor
$T_{cell,t}$	Cell temperature at time t
$T_{cell,STC}$	Cell temperature at standard test conditions
SOC	Ratio of the remaining battery charge to the rated capacity
μ	Self-discharge rate of the battery
$P_{ch,t}$	Battery charging power at time t
$P_{dis,t}$	Battery discharging power at time t
η^{ech}	Battery charging efficiency
η^{edis}	Battery discharging efficiency
Q^{ES}	Installed battery capacity
$S_{i,t}$	Operating status of unit i at time t
$t_i^{start,new}$	Start time of load i after demand response
$t_i^{end,new}$	End time of load i after demand response
$t_i^{start,old}$	Start time of load i before demand response
$t_i^{end,old}$	End time of load i before demand response
a	Time-shiftable load categories
$P_{i,N}$	Rated power of load i
P_i	Load i power consumption
$Fac_{j,t}$	The value of the j_{th} trigger element at time t
$Fac_{j,set}$	Setting value of the j_{th} trigger element
b	Triggered “on-off” load categories
$P_{grid,t}$	Power purchased from the grid at time t
$f_{g,t}$	Time-sharing tariff
C_{PV}	Cost of photovoltaic power generation
$C_{b,t}$	Battery charging and discharging costs
$C_{PV,sell}$	Photovoltaic power feed-in tariffs
SOC_{min}	Minimum battery state of charge
SOC_{max}	Maximum battery state of charge
$P_{PV,sell}$	Photovoltaic selling power at time t
$P_{Load,t}$	Load power at time t
$P_{b,t}$	Battery charging and discharging power
$P_{PV-load}$	Source-load power difference
$P_{ch,t}$	Battery charging power at time t
$P_{dis,t}$	Battery discharging power at time t
$P_{ch,max}$	Maximum battery charging power
$P_{dis,max}$	Maximum battery discharging power
$P_{PV,max}$	Maximum power of PV power generation

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1. INTRODUCTION

With the development of the global economy and the rise in health awareness, aquatic animals have become a food sector of great interest as an important channel for obtaining animal proteins [1]. Aquaponics systems have been shown to be a self-sustainable, cost-effective and eco-friendly method of urban farming, combining recirculating aquaculture systems with hydroponics for wastewater treatment and resource recycling, replacing up to 10% of the total water per day, and contributing to the large-scale production of fish and thus meeting the demand for animal protein caused by population growth [2-3]. Urban aquaponics farms need energy to power various devices and equipment including water pumps, heat pumps, heaters, aerators, air conditioning, and LED lighting. Currently, aquaponics farms spend a large percentage of their total operating costs on electricity due to the wide variety of electrical equipment and a single energy supply method [4]. Minimizing energy consumption to the greatest extent possible in aquaponics systems presents a highly challenging task [5].

Some studies are dedicated to developing energy-efficient technological strategies to reduce energy consumption. Existing research [6] proposed a new heating method using a combination of a helical coil heat exchanger and thermal energy storage units to replace electric heaters for low-energy heating measures. Researchers from [7] used waste heat from a cogeneration system to heat a greenhouse aquaponics system to reduce energy consumption.

Renewable energy supply is also an effective solution to reduce the fossil fuel consumption of industrial aquaponics farming. Researchers from [8] proposed that the commercial model of fishery photovoltaic (PV) complementary systems can improve the operational efficiency of solar PV enterprises and the economic benefits of aquaculture. Gina Patricia Suárez-Cáceres et al. showed that thermo-solar panels and bio-fertilizing alternatives can help save fossil energy [9]. Study in [10] performed energy modeling of a greenhouse covered with translucent PV, where the PV system transmits a portion of daylight and provides some shading and solar power generation.

With new energy efficient technologies, increased penetration of renewable energy sources such as PV panels, and increased adoption of high power appliances, demand response (DR) programs have become an important part of lowering net demand, reducing energy bills for aquaculture researchers, and increasing the penetration of distributed solar energy. A DR strategy coordinating the total power exchange between the greenhouse network and the main power grid is proposed in [11]. Researchers from [12] demonstrate the effectiveness of DR in optimizing energy savings in the operation of aquaponics system equipment.

Existing studies on energy consumption mostly focus on greenhouse modeling and partial modeling of large-scale industrial aquaponics, lacking comprehensive research on the overall energy consumption of aquaponic systems. Furthermore, there has been limited investigation into energy management schemes that optimize the synergy between renewable energy source generation and demand-side response in agricultural scenarios. In this paper, we studied grid-connected industrial aquaponics equipped with PV and battery energy storage units. This model is designed to minimize the operating cost and increase the local renewable energy penetration. The main contributions of this paper are listed as follows:

(1) The dispatchable units of the urban aquaponics farm are classified and modeled by analyzing the flexibility characteristics of the dispatchable units.
(2) To minimize operating costs and source-load power difference, a DR-based source-load dispatch method is proposed, which can optimize the unit operation scheme and battery storage charging and discharging activities.
(3) Scenarios for typical days in winter and summer are generated and the model is validated by example simulations to verify the effectiveness of the proposed method.

2. MATERIAL AND METHODS

2.1 Aquaponics system equipment composition and classification

There is a wide variety of aquaponics farm equipment, and each asset can be classified into one of two categories based on load flexibility characteristics: non-dispatchable and dispatchable. Non-dispatchable loads cannot be reprogrammed arbitrarily with operating times and operating status, including UV lamps, water pumps, illumination lamps, circulation fans, etc. Loads that can be rescheduled daily based on factors such as real-time PV storage output and time-of-use electricity rates include two types: time-shiftable loads (baiter, irrigation pumps) and triggered “on-off” loads (ventilators, aerators, heat pumps, wet curtain pumps, and heating rods). The specific schematic diagram of the aquaponic system equipment scenario is shown in Fig. 1.

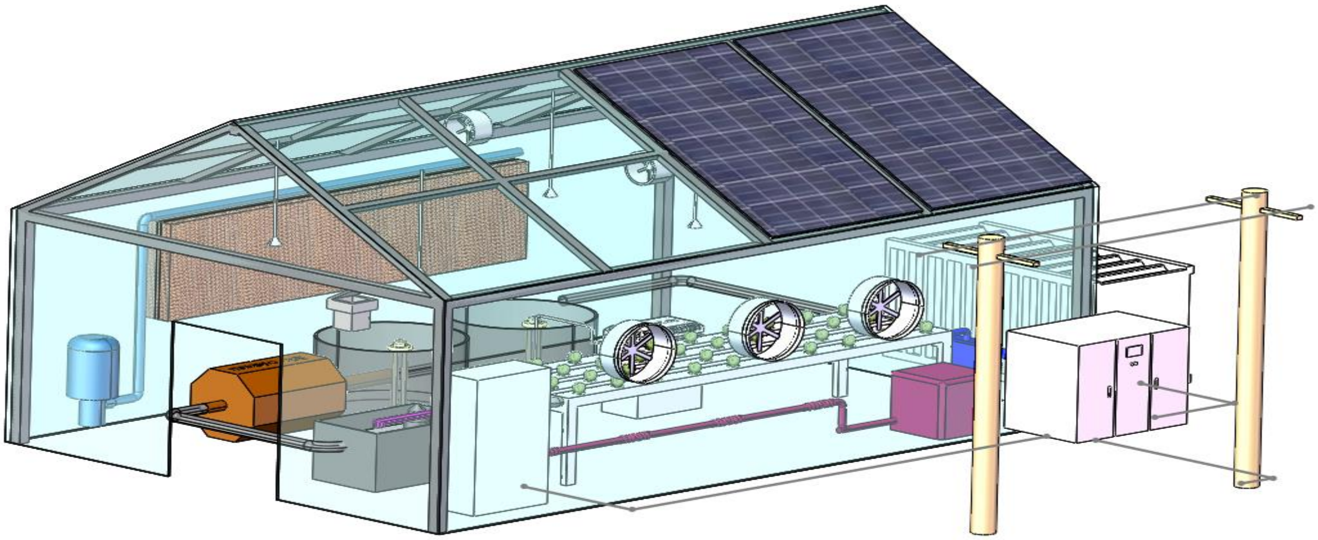

Fig. 1 Aquaponics farm equipment and energy supply structures

2.2 PV-battery model

2.2.1 PV power generation

The meteorological factors for the power output of the PV modules mainly include incident irradiance G_t, spectral coefficients *SF*, thermal factor *TF*, parameters of standard conditions, and ambient temperature. *P** and *G** identified the maximum power and global irradiance at standard test conditions. The power generated by the PV modules ($P_{PV,t}$) can be expressed in (1). The thermal factor is calculated from the efficiency temperature coefficient γ of the PV material by Eq. (2). The spectral coefficients of the spectral unit are dimensionless and the values can be found in [13].

$$P_{PV,t} = P^* \cdot G_t \cdot TF \cdot SF / G^*, \forall t \in \Omega \tag{1}$$

$$TF = 1 + \gamma \cdot (T_{cell,t} - T_{cell,STC}) \tag{2}$$

2.2.2 Energy storage model

The battery model is processed using a linear model, taking into account the self-loss and charging/discharging efficiency of the battery. The state of charge (*SOC*) is an important parameter of a battery, indicating the ratio of the remaining battery charge to the rated capacity. Accurate estimation of the state of charge is critical for battery management systems to help determine the state of charge and discharge of a battery, ensure safe battery operation, and optimize service life, which can be expressed in (3).

$$\begin{aligned} SOC_t &= (1-\mu)SOC_{t-1} + P_{ch,t}\eta^{ech}\Delta t / Q^{ES} \\ &- P_{dis,t}\Delta t / (Q^{ES}\eta^{edis}), \forall t \in \Omega \end{aligned} \tag{3}$$

2.3 Appliance response model

Schedulable load means that electricity demand can be adjusted within a certain range, which helps the system improve the efficiency of electricity consumption. In this paper, according to the characteristics of power consumption of various types of equipment in aquaponics systems, the dispatchable loads are divided into two categories: time-shiftable loads and triggered “on-off” loads.

2.3.1 Time-shiftable loads

For time-shiftable loads, the operating time must meet the duration requirement before stopping work, and the working period can be appropriately scheduled. This type of load scheduling method is illustrated in Fig. 2, where the effective operating interval of the load is predetermined before energy optimization. Based on the optimization objectives, suitable operating time slots are selected to meet the user's demand response goals. The model is shown as follows.

$$S_{i,t}^a = \begin{cases} 1, & t_i^{start,new} \le t \le t_i^{end,new} \\ 0, & otherwise \end{cases}, \forall t \in \Omega \tag{4}$$

$$\sum_{t=t_i^{start,ava}}^{t_i^{end,ava}} S_{i,t}^a = t_i^{end,old} - t_i^{start,old} + 1 \tag{5}$$

$$t_i^{start,ava} \le t_i^{start,new} < t_i^{end,new} \le t_i^{end,ava} \tag{6}$$

$$P_i^a = (P_{i,N} . S_{i,t}^a)/4 \tag{7}$$

2.3.2 Triggered “on-off” loads

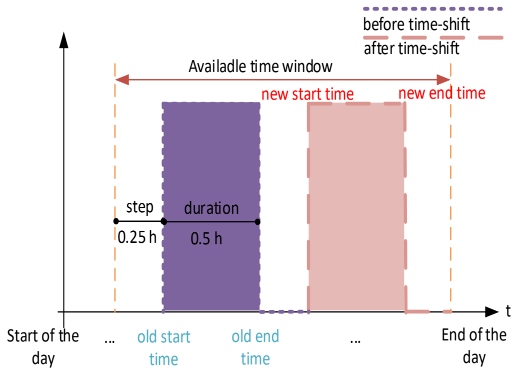

Fig. 2 Schematic diagram of the time-shiftable load optimization operation process

The operation of triggered "on-off" loads is influenced by the operating environment and their operating periods are not predetermined before optimization but are mainly constrained by trigger factor set values. For instance, devices like air conditioners start operating when the ambient temperature arrive the maximum set value and stop when it reaches the minimum value. The trigger process is illustrated in Fig. 3. The trigger-based load model is as follows.

$$S_{i,t}^{b}=\begin{cases}1, & Fac_{j,t}<Fac_{j,set} \\ 0, & otherwise\end{cases}, \forall t\in\Omega, \forall j\in J \qquad (8)$$

$$P_{i}^{b}=(P_{i,N}.S_{i,t}^{b})/4 \qquad (9)$$

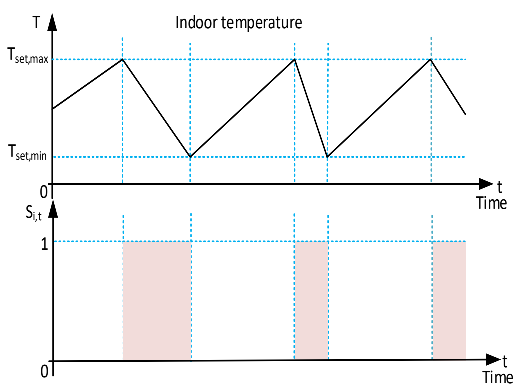

Fig. 3 Schematic diagram of the triggered "on-off" load optimization operation process

2.4 Energy management optimization model under demand response

The paper builds an energy management optimization model for urban aquaponic farms under demand response by utilizing the basic load information of aquaponic systems, coupled with the interdependent relationship between fish and vegetable physiological characteristics. This is combined with the output model of PV-battery and equipment response model. The aim is to obtain the most cost-effective operational strategy for daily equipment operation.

2.4.1 Optimization objective

Adopting the operating cost and source-load power difference as the optimization objective, while ensuring the source-load matching degree, comprehensively considering the surplus power on-grid revenue and grid power purchase cost, the objective function is expressed as Eq. (10). α_1 and α_2 are steel balancing factors.

$$\min\{\alpha_1 P_{PV-load}+\alpha_2 F\} \qquad (10)$$

$$P_{PV-load}=\sum_{t\in\Omega}\left|P_{PV,t}+P_{dis,t}-P_{ch,t}-P_{Load,t}\right| \qquad (11)$$

$$F=\sum_{t\in\Omega} f_{g,t}\cdot P_{grid,t}+P_{PV,t}\cdot C_{PV}+\left|P_{b,t}\right|\cdot C_b-P_{PV,sell}\cdot C_{PV,sell}, \forall t \qquad (12)$$

2.4.2 Constraints

Equations (4-6) are time-shiftable load response constraints and (8) are triggered load response constraints. Equation (11) is the power balance constraint after adding PV-storage, (12) is the SOC value constraint, (13) and (14) are the battery charging and discharging power limits, respectively, (15) sets the battery cannot be charged and discharged simultaneously, (16) is the PV power generation constraint.

$$P_{Load,t}-P_{PV,t}-P_{b,t}=P_{grid,t}, \forall t\in\Omega \qquad (13)$$

$$SOC_{min}\le SOC_t\le SOC_{max} \qquad (14)$$

$$0\le\left|P_{ch,t}\right|\le P_{ch,max} \qquad (15)$$

$$0\le P_{dis,t}\le P_{dis,max} \qquad (16)$$

$$P_{ch,t}\cdot P_{dis,t}=0 \qquad (17)$$

$$0\le P_{PV,t}\le P_{PV,max} \qquad (18)$$

3. RESULTS AND DISCUSSION

3.1 Case study setup

The aquaponics farm scenarios considered in this study are shown in Fig. 4. Typical days in winter (December) and summer (July) were selected for the analysis, and the temperature as well as the irradiance of the typical days are shown in Fig. 5. The duration of irradiance on a typical day in summer is 15 hours compared to only 10 hours in winter. The model time step is 15 minutes. α_1 and α_2 take values of 0.01 and 1, respectively. The programming environment for the overall constructed model was Spyder (Python 3.9), running on a desktop computer with an Intel Core i5-12400 2.50 GHz CPU and 16 GB of RAM.

Fig. 4 Example scenario of an aquaponics farm

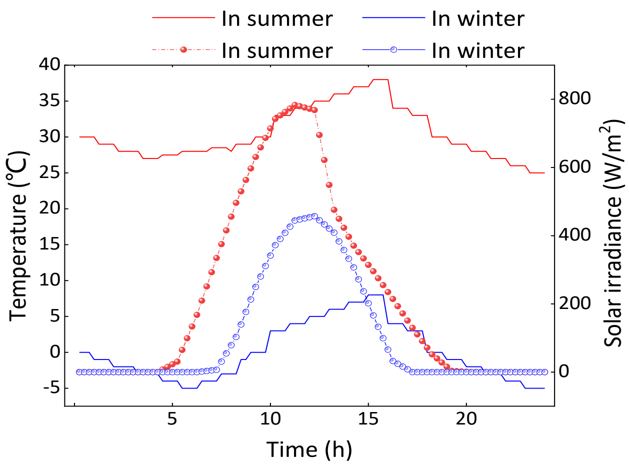

Fig. 5 Typical daily temperature and irradiance

3.2 Demand Response Optimization Performance

The simulation results of optimal energy scheduling for typical days of a PV-battery integrated urban aquaponics farm under demand response are shown in Fig. 6. From Fig. 6(a), it can be seen that on a typical summer day, some of the peak loads from 10:00 A.M.-08:00 P.M. are partially curtailed and partially time shifted to 00:00 A.M.-05:00 A.M. after optimization. In Fig. 6(b), it is shown that after optimization, the operating periods of the load exhibit a slight periodicity. The typical daily solar power generation can meet the load operating periods for approximately 11 hours and 6 hours, respectively. The source-load matching is taken into account along with load curtailment. Moreover, during peak periods, the generated electricity far exceeds the demand, leading to surplus electricity being fed back into the grid, thereby generating certain revenue and contributing to reduce daily operational costs.

Table 1 provides sufficient evidence of the effectiveness of the proposed algorithm. It demonstrates that during typical summer days, the algorithm can reduce operating costs to 189.2 CNY, accounting for a 33.4% share, while during typical winter days, it can reduce operating costs to 445.1 CNY, achieving a 27.2% share. This reduction leads to a decrease in purchased electricity from the grid to 133.8 kWh and 487.6 kWh, respectively.

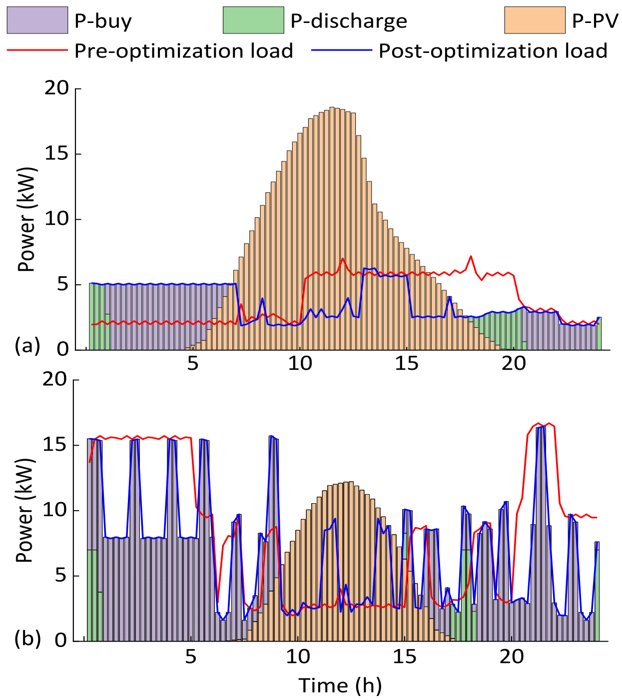

Fig. 6 Load before and after optimization on a typical day: (a) in summer; (b) in winter

Table. 1 Economics of scenario optimization results

Comparison of typical day scenarios	Pre-optimization	Post-optimization
Summer electricity purchase (kWh)	367.2	133.8
Summer electricity purchase costs (CNY)	284.1	189.2
Winter electricity purchase (kWh)	790.4	487.6
Winter electricity purchase costs (CNY)	611.7	445.1

Table 2 shows the results of source-load matching under the installed capacity of 25 kW PV panels and 10.4 kW of energy storage, with a typical daily energy consumption of 345.8 kWh in summer, and energy transfer through the battery of 29.6 kWh. Typical daily energy consumption in winter is 673.7 kWh, and the optimized load distribution promotes PV power generation consumption during the daytime, totaling 169.7 kWh, and 31.5 kWh of energy transferred through the storage battery. The reason why the optimized loads are not fully concentrated shifted to the peak hours of PV generation is limited by the requirements of the environment in which fish and vegetables are grown.

Table. 2 Source-load matching results

Parametric	Typical summer day	Typical winter day
Total load (kWh)	345.8	673.7
PV energy supply (kWh)	199.6	169.7
Battery discharge (kWh)	42.0	47.9
Battery charge (kWh)	29.6	31.5

4. CONCLUSIONS

This article addresses the current issues of high energy consumption and limited energy supply methods in urban aquaponic farms. It constructs a source-load real-time energy management model for integrated urban aquaponic farms based on demand response, through detailed analysis of the farm's load. This model includes PV energy storage and load response modules. Through actual scenario simulations, it has been verified that the proposed model's derived equipment rescheduling schemes significantly reduce purchased electricity, operating costs, and source-load matching. In the future, we will extend the existing base and consider the participation of urban aquaponics farms in ancillary services in the electricity market.

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