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An Integrated Energy System Operation Optimization Model for Water Consumption Control Analysis in Park Scale from the Perspective of Energy–Water Nexus

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Abstract: The water–energy nexus has become a key factor in the implementation of low-carbon green development, which has led to the need for exploring effective management within the coupled integrated system with multi-energy flow supplies. In this study, the coupled relationship between water resources and energy in the integrated energy system was systematically analyzed, and a system operation optimization model was proposed through comprehensively considering cold, heat and electricity load, and nine kinds of energy conversion and supply equipment/technology from the perspective of a water resources and energy nexus in a typical industry park. The system operation scheme, energy supply mode, net benefit and water resource consumption under different water resource control scenarios were obtained. The results show that water resource control would directly bring about a directly positive influence on renewable energy utilization and energy storage reduction, and that a system's external dependence and benefits, renewable energy utilization potential and other factors in an integrated energy system should be comprehensively considered. The development of more effective control indicators could be better to promote the effectiveness of bidirectional regulation in a water–energy nexus.

Keywords: water–energy nexus; integrated energy system; operation optimization; water consumption control

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Citation: Gou, R.; He, G.; Yu, B.; Xiao, Y.; Luo, Z.; Xie, Y. An Integrated Energy System Operation Optimization Model for Water Consumption Control Analysis in Park Scale from the Perspective of Energy–Water Nexus. *Energies* **2022**, *15*, 4410. https://doi.org/10.3390/en15124410

Academic Editor: Helena M. Ramos

Received: 23 March 2022
Accepted: 11 May 2022
Published: 16 June 2022

1. Introduction

As important material resources in supporting society's continuous development, the water–energy nexus has gradually focalized energy resource utilization and eco-friendly, low-carbon development [1–4]. The feedback relations, mutually between water and energy, would be comprehensively considered and integrated into system optimization management and decision-making processes—an important measure for promoting sustainable development. As clean energy technologies advance, the integrated energy system has become a significant energy supply mode for supporting local clean energy consumption in recent years [5,6]. Complementary coupled multi-energy flow and comprehensive energy supply in the integrated energy system lead to multiple interactions between water and energy and multiple complexities in resource management that directly alter the effectiveness of system operations under water- and energy-saving pressures [7,8]. Therefore, it is necessary to clarify the interaction of water and energy and to explore the co-operating strategy of multiple energy streams from the water–energy nexus within the integrated energy system.

In recent years, many researchers have paid attention to water footprint and water-saving assessments in energy system development and utilization [9–12]. For example, Li et al. (2012) systematically analyzed carbon emission reduction and water resource consumption in wind power generation [13]. Wang et al. (2017) advanced the input–output analysis method to evaluate water resources and energy consumption in the energy industry, through analyzing the intensity of direct and indirect water resource consumption within energy production [14]. Wang et al. (2018) summarized the water consumption and water-saving potential of various power generation modes, as well as the water–energy–environment nexus in the power industry [15]. Den et al. (2018) made a deep analysis of water use efficiency performance for microelectronics manufacturing facilities in Taiwan's Science Parks [16]. Luna et al. (2019) developed a hybrid optimization model for improving energy efficiency in water supply systems, in order to push towards more sustainable water management concerning the water–energy nexus [17]. From the perspective of social economic networks, Peng et al. (2018) proposed an accounting framework for energy–water nexus network analysis in Hubei Province, through an input–output and ecological network analysis [18]. Ji et al. (2020) developed a regional low-carbon power system planning model to consider the effects of water resource consumption within the process of energy development and utilization in Shandong Province, China [19].

In general, the above studies carried out in-depth analyses on the water–energy nexus on a regional macroscale. However, regarding an integrated energy system, an integrated multi-energy flow (electricity–gas–heat–cold) system was constructed on a small scale (an industrial park), along with more concomitant water resource consumption [20–23]. In addition, various system optimization models were developed for different integrated energy system operation managements, and more attention was paid to the energy resource allocation and the complementarity of multi-energy flow in the integrated energy system [24–26]. Moreover, the synergy and constraint between water and energy resources were not taken into account, making it difficult to maximize the effectiveness of resource elements in the integrated energy system [27].

Therefore, the aim of this study is to propose an operation optimization model by comprehensively analyzing the energy–water nexus nodes and energy–water nexus effects in an integrated energy system on an industry park scale. The main work includes: (1) making a comprehensive analysis of the water–energy nexus in the typical integrated energy system of an industrial park; (2) developing a system operation management model with the objective of gaining the maximum net benefit from the water–energy nexus; and (3) generating the optimal system energy supply scheme that operates under different scenarios. A typical integrated energy system in an industrial park was developed considering cold, heat and electricity load, and nine kinds of energy conversion and supply equipment/technology. Energy–water nexus relationships in the park's integrated energy system were systematically analyzed. The constraint of water resources on the integrated energy system operation and the energy–water interaction management mechanism were obtained to support the low-carbon and efficient utilization of resources in the integrated energy system.

2. Power–Gas–Water Nexus in Integrated Energy System

2.1. Integrated Energy System Framework in Park

Figure 1 shows the schematic diagram of an integrated energy system in a typical industry park. It mainly includes a wind turbine unit, photovoltaic unit, a gas triple-supply system (cooling, heating, and electricity), energy storage, electric refrigeration, an electric boiler, and power-to-gas (P2G) coupling facilities. The whole system integrates multiple types of energy conversions, so as to maximize the utilization efficiency of energy resources. The electricity load demand is satisfied by wind power generation, solar power generation, gas power generation, and external power grid supply; cooling load demand is satisfied mainly from electric refrigeration and a triple-supply system; and heat load demand is supplied by an electric boiler and a triple-supply system.

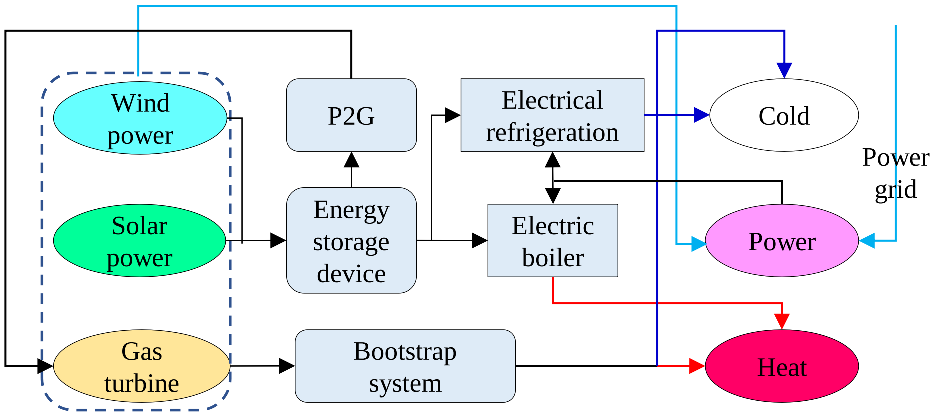

Figure 1. Integrated energy system architecture in an industrial park.

2.2. Water–Energy Nexus

In the integrated energy system, the consumption of water resources is the main node of the water–energy nexus. Gas cooling, heating, and an electricity triple-supply system are most typical in a gas–electric–water nexus system [18–22]. The processes of converting gas into electricity (gas unit) and waste heat into cold and heat (refrigeration unit and heat exchange unit) are performed along with the processes of water resource discharge, consumption, and circulation cooling. As important production elements, water resources are associated with the gas–electric–cooling–heat conversion process. As a renewable energy power generation technology, P2G takes water resources and CO_2 as input factors to convert surplus electricity from renewable energy power generation into natural gas (mainly methane). In this process, P2G consumes water resources and electricity to produce a natural gas that is a nexus of water–electricity–gas. Refrigeration is powered by an electric and circulating medium of water, and this process realizes the conversion from electricity to cold through a series of complex energy exchanges and material transfers, which are the nexus of electricity–water–cold, whilst an electric boiler is the electricity–water nexus node.

3. Model Development

3.1. System Cost Model

The cost of a comprehensive energy system in the industrial park mainly includes operation costs, gas purchasing costs, and power purchasing costs.

(1) Operation costs

$$C_{operation} = \sum_{i=1}^{n} \sum_{t=1}^{T} OP_{it} \cdot CO_i \tag{1}$$

where, OP_{it} is the output of unit i at time t, where T is the total operation time during one day. CO_i denotes the operation cost of unit output of unit I, where N is the number of energy supply technology. i = 1 for wind power unit (PW_t), i = 2 for photovoltaic unit (PS_t), i = 3 for gas power unit (PG_t), i = 4 for waste heat heating (PGH_t), i = 5 for waste heat refrigeration (PGC_t), i = 6, for electric refrigeration (ETH_t), i = 7 for electric boiler (ETC_t), i = 8 for P2G ($P2G_t$), and i = 9 for energy storage equipment (PSC_t).

(2) Gas purchasing costs

$$C_{gas} = \sum_{t=1}^{T} GQ_t \cdot CG_t \tag{2}$$

where, GQ_t is the consumption amount of natural gas at time t, and CG_t denotes the natural gas prices at time t.

(3) Power purchase cost

$$C_{electric} = \sum_{t=1}^{T} GE_t \cdot CE_t \tag{3}$$

where, GE_t denotes the purchased electricity amount at time t, and CE_t is the electricity price at time t.

3.2. System Revenue Model

The benefits of the integrated energy system mainly include the profits from selling electricity, heat, and cold.

(1) Revenue from electricity sales

$$B_{electric} = \sum_{t=1}^{T} BIE_t \cdot E_t \tag{4}$$

where, BIE_t is the electricity selling price at time t, and E_t is the power consumption amount at time t.

(2) Revenue from heat sales

$$B_{heat} = \sum_{t=1}^{T} BIH_t \cdot H_t \tag{5}$$

where, $BIH_t^{\pm}$ denotes the heat price at time t, and $H_t^{\pm}$ is the heat load at time t.

(3) Revenue from cool sales

$$B_{cool} = \sum_{t=1}^{T} BIC_t \cdot C_t \tag{6}$$

where, $BIC_t^{\pm}$ represents the cool price at time t, and $C_t^{\pm}$ denotes the cooling load at time t.

3.3. Integrated Energy System Optimization Model

3.3.1. Objective Function

The objective of the integrated energy system optimization model on an industrial park scale is to maximize net profit, and the objective function is expressed as follows:

$$\begin{aligned} Max\, f &= B_{electric} + B_{heat} + B_{cool} - C_{operation} - C_{gas} - C_{electric} \\ &= \sum_{t=1}^{T} BIE_t \cdot E_t + \sum_{t=1}^{T} BIH_t \cdot H_t + \sum_{t=1}^{T} BIC_t \cdot C_t - \sum_{i=1}^{n}\sum_{t=1}^{T} OP_{it} \cdot CO_i - \sum_{t=1}^{T} GQ_t \cdot CG_t - \sum_{t=1}^{T} GE_t \cdot CE_t \end{aligned} \tag{7}$$

3.3.2. Constraint

(1) Demand and supply balance of cold, heat, and electricity load

Energy demand for cold, heat, and electricity in an industrial park can be satisfied by different technologies, and the demand and supply balance would be kept to guarantee normal system operation.

$$E_t = PW_t + PS_t + PG_t + GE_t - SIE_t - IEH_t - IEC_t \tag{8}$$

$$H_t = PGH_t + ETH_t \tag{9}$$

$$C_t = PGC_t + ETC_t \tag{10}$$

where, SIE_t is the input power of energy storage equipment. IEH_t and IEC_t denotes the power supply for electric boiler and refrigeration. PGH_t and PGC_t are the heat and cold output of gas tri-generation unit. ETH_t and ETC_t denote the heat output from electric boiler and cold output from electric refrigeration equipment.

(2) Operation constraints of wind power unit

$$PW_{\min t} \leq PW_t \leq PW_{\max t}, \forall t \tag{11}$$

where, $PW_{\min t}$ and $PW_{\max t}$ represent the minimum and maximum availability of wind energy resources.

(3) Operation constraints of photovoltaic unit

$$PS_{\min t} \leq PS_t \leq PS_{\max t}, \forall t \tag{12}$$

where, $PS_{\min t}$ and $PS_{\max t}$ represent the minimum and maximum availability of photovoltaic resources.

(4) Operation constraints of the gas tri-generation unit

For the gas tri-generation unit, gas, heat, cold, and electric power are integrated within a general system, and energy conservation in resource conversion and utilization is the basic principle.

$$PG_t = (SEPG_t \cdot \gamma + GQ_t) \cdot \alpha, \forall t \tag{13}$$

$$PG_t \cdot \beta = PGC_t \cdot \eta + PGH_t \cdot \mu, \forall t \tag{14}$$

$$PG_{\min t} \leq PG_t \leq PG_{\max t}, \forall t \tag{15}$$

$$PGC_{\min t} \leq PGC_t \leq PGC_{\max t}, \forall t \tag{16}$$

$$PGH_{\min t} \leq PGH_t \leq PGH_{\max t}, \forall t \tag{17}$$

$$PG_t = (SEPG_t \cdot \gamma + GQ_t) \cdot \alpha, \forall t \tag{18}$$

where, $SEPG_t$ is the energy consumption of P2G. γ represents the technical conversion factor of P2G. α is the conversion coefficient of natural gas power generation. β denotes the waste heat output per unit of generating capacity of gas generating unit. μ and η are the waste heat consumption per unit of refrigeration and production heat. $PG_{\min}$ and $PG_{\max}$ are the minimum and maximum output of gas set. $PGC_{\min}$ and $PGC_{\max}$ denote the minimum and maximum cooling output of waste heat utilization system. $PGH_{\min}$ and $PGH_{\max}$ are the minimum and maximum output of waste heat utilization system.

(5) Operation constraints of P2G

For the gas tri-generation unit, gas, heat, cold, and electric power are integrated within a general system, and energy conservation in resource conversion and utilization is the basic principle.

$$P2G_t = SEPG_t \cdot \gamma, \forall t \tag{19}$$

$$P2G_{\min t} \leq SEPG_t \cdot \gamma \leq P2G_{\max t}, \forall t \tag{20}$$

where, $P2G_{\min}$ and $P2G_{\max}$ represent the minimum and maximum output of P2G.

(6) Operation constraints of the electric boiler and electric refrigeration

For the electric boiler and electric refrigeration, the energy demands are supplied by the energy storage output and electric power.

$$SEH_t + IEH_t = ETH_t, \forall t \tag{21}$$

$$SEC_t + IEC_t = ETC_t, \forall t \tag{22}$$

$$ETH_{\min t} \leq ETH_t \leq ETH_{\max t}, \forall t \tag{23}$$

$$ETC_{\min t} \leq ETC_t \leq ETC_{\max t}, \forall t \tag{24}$$

where, SEH_t and SEC_t denote the electric boiler and electric refrigeration output that powered by energy storage output. $ETH_{\min}$ and $ETH_{\max}$ are the minimum and maximum output of electric boiler. $ETC_{\min}$ and $ETC_{\max}$ represent the minimum and maximum output of electric refrigeration.

(7) Operation constraints of energy storage facilities

For energy storage facilities, the input and output balance and the minimum and maximum energy storage in each period would all be considered to a guarantee safe and reliable movement of facilities.

$$SCE_t = SCE0, \forall t = 1 \tag{25}$$

$$SCE_t = SCE_{t-1} + SIE_t - SEPG_t - SEH_t - SEC_t, \forall t \geq 2 \tag{26}$$

$$PSC_t = \begin{cases} SIE_t, & if \;\; SCE_t \geq SCE_{t-1}, \forall t \geq 2 \\ SEPG_t + SEH_t + SEC_t, & if \;\; SCE_t \geq SCE_{t-1}, \forall t \geq 2 \end{cases} \tag{27}$$

$$SCE_{\min t} \leq SCE_t \leq SCE_{\max t}, \forall t \tag{28}$$

where, $SCE0$ is the initial energy storage of energy storage equipment. SCE_t denotes the energy storage of energy storage equipment at time t. $SCE_{\min}$ and $SCE_{\max}$ are the minimum and maximum energy storage.

(8) Water resource constraints

The water consumption index is considered for water conservation control in the integrated energy system and generates more optimization schemes under the water–energy nexus.

$$\left\{ \begin{array}{l} PW_t \cdot WW + PS_t \cdot WS + PG_t \cdot PG + PGC_t \cdot WGC + PGH_t \cdot WGH \\ +P2G_t \cdot WPG + ETH_t \cdot WEH + ETC_t \cdot WEC \end{array} \right\} \leq (E_t + H_t + C_t) \cdot TWC \tag{29}$$

where, WW, WS, WG, WGC, WGH, WPG, WEH, and WEC respectively represent the water consumption intensity of wind turbine, photovoltaic unit, gas turbine, waste heat utilization refrigeration and heating, P2G, electric boiler and electric cold. TWC is the water resource consumption control index of per energy consumption in the industry park integrated energy system.

4. Results and Discussion

4.1. Overview of the Integrated Energy System

An industrial park is taken as a case study, and the integrated energy system is shown in Figure 1. The installed capacity of the various equipment for the integrated energy system is shown in Table 1, equipped with WPP (130 MW), PV (50 MW), ESD (10 MW), GT (20 MW), WHB (25MW), AC (15MW), HE (25MW), and ECC and equipped with ER (15 MW), EB (15 MW), P2G (15 MW), and GSD (35 MW).

Table 1. Installed capacity of various operating equipment for the integrated energy system.

Equipment	Capacity	Equipment	Capacity
Wind turbine unit	24 MW	Gas generator	20 MW
Photovoltaic units	30 MW	Waste heat cooling	10 MW
P2G	12 MW	Waste heat heating	20 MW
Energy storage	10 MW	Electric Boiler	15 MW
Electric refrigeration	15 MW		

Based on the system operation analysis, the daily cooling, heating, and electricity load demand for each time was obtained, as shown in Figure 2a. The typical daily wind and solar power supply can be obtained through analyzing the meteorological data in the location, as shown in Figure 2b. Water resource consumption intensity control of the integrated energy system in the park was set as: 'no water resource dissipation control' (scenario S0), 'water resource dissipation intensity 0.3 L/kwh' (scenario S1), '0.25 L/kwh' (scenario S2), and '0.2 L/kwh' (scenario S3). In order to make full use of the demand-side resources and promote new energy consumption, the time-of-use price of electricity, heat, and cold were introduced with the function of stimulating and encouraging energy users to shift peak, fill valley and optimize the power consumption mode. Table 2 presents the time-of-use prices of different energy supply types in the energy system.

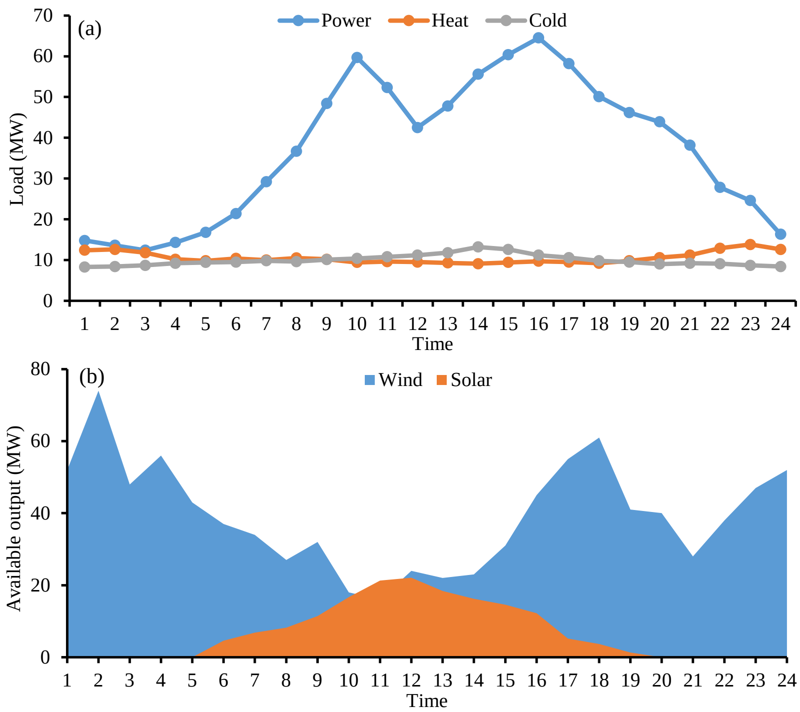

Figure 2. Load demand (**a**) and available resource amounts (**b**) in industrial park.

Table 2. The time-of-use prices of different energy supply types in the integrated energy system.

	Period	Price (10^3/MWh)
Electricity	00:00–06:00	0.32
	06:00–10:00	1.10
	10:00–13:00	0.67
	13:00–17:00	1.10
	17:00–22:00	0.67
	22:00–24:00	0.32
Heat	00:00–05:00	0.28
	05:00–08:00	0.48
	08:00–11:00	0.65
	11:00–17:00	0.48
	17:00–20:00	0.65
	20:00–24:00	0.28
Cold	00:00–24:00	0.22
Imported power	00:00–06:00	0.34
	06:00–10:00	1.20
	10:00–13:00	0.71
	13:00–18:00	1.20
	18:00–22:00	0.71
	22:00–24:00	0.34

4.2. Results Analysis and Discussion

Figure 3 presents the optimized output from wind, photovoltaic, and gas generation units under the S2 scenario. In general, the photovoltaic unit would generate the maximum output during the whole operation cycle (0:00–24:00), and the wind turbine would maintain the maximum output from 04:00 to 23:00. However, compared with wind and photovoltaic units, the output of gas-fired units would have a little volatility. The maximum output was 16.1 MW, which appeared in 14:00–15:00, and the minimum output of 5 MW would be in 22:00–7:00. Comparing the output of different units, the results indicate that the wind power output unit would have the largest output, and clean energy would be greatly utilized in each time-period. In addition, the output of the gas turbines unit would have a little fluctuation during the whole load supply period, and this would ensure comprehensive supply security for the energy system. In the integrated energy system, renewable energy could be utilized to an extreme for suppyling multiple energy flows, and the traditional power generation technologies would play subsidiarity as security assurance rulers.

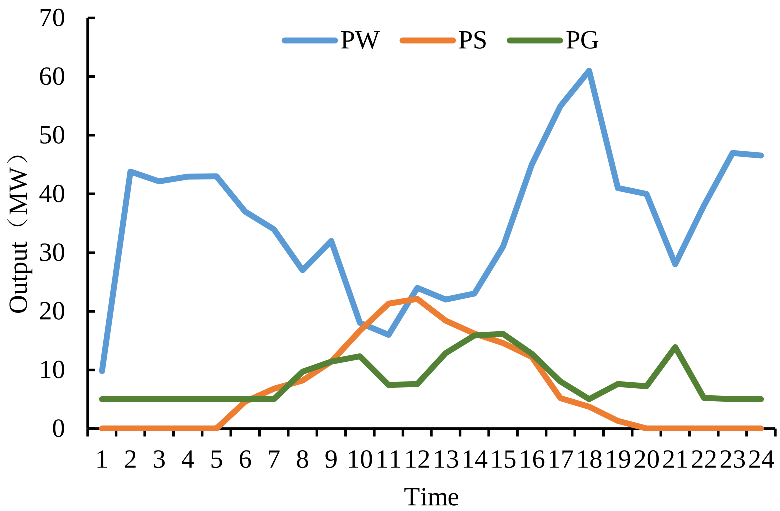

Figure 3. The optimized output of wind power, solar power, and natural gas power.

Figure 4 shows the optimized supply schemes for cold and heat under the S2 scenario. Regarding heat supply, there would be little difference between the waste heat output and electric heat output from 23:00 to 8:00. During the above-mentioned period, the waste heat output could remain at 5.77 MW, and the electric heat output would show a decreasing trend. In addition, the maximum output would be 8.08 MW (23:00–24:00), and the minimum output would be 4.03 MW (5:00–6:00). However, from 8:00 to 23:00, there would be greater fluctuations in the output of waste heat and electric heat. For example, the waste heat output would be 0 at 11:00–13:00, 18:00–21:00, and 22:00–23:00, and the maximum output would be 9.4 MW from 15:00 to 16:00. The maximum output of electric heat would be 12.9 MW (22:00–23:00), and the minimum output would be 0 at 10:00–11:00 and 14:00–16:00. Furthermore, for the cooling load supply, electric refrigeration would be mainly used to meet the cooling load demand, and the output of waste heat refrigeration would be 0 from 23:00 to 8:00. In general, the waste heat refrigeration would start to operate from 8:00, and the output would reach to 10 MW from 13:00 to 18:00. Until 23:00, the waste heat refrigeration would be used as the main cooling load supply mode. From the above analysis, in order to satisfy multiple energy demands, all of the technologies in the integrated energy system would have to operate smoothly, and the supply fluctuations for each technology would be mainly introduced by demand and the random character of available wind and solar energy resources that cause the system changes.

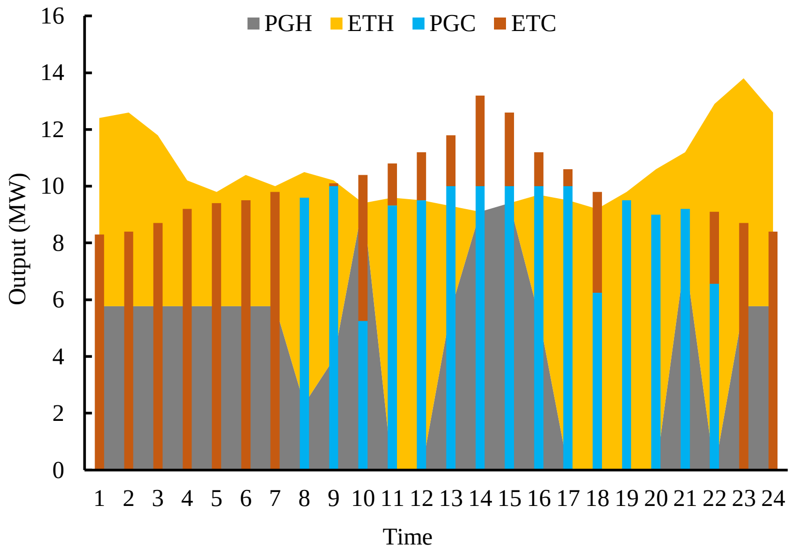

Figure 4. The cold and heat supply schemes under S2 scenario.

Figure 5 describe the output of gas turbines, wind turbines, photovoltaic units, and the purchased power amount under different water resource constraints. Obviously due to strengthening water consumption restrictions, the output of gas-fired power generation would gradually decrease due to the high intensity of water consumption. Compared to the S2 and S3 scenarios, the output of the gas-fired power unit would be 5 MW from 23:00 to 8:00, and the output of gas-fired power in the S3 scenario would be less than that of the S2 scenario in other periods. In addition, the water consumption from wind power generation would be slightly higher than that from photovoltaic power. The overall output of the photovoltaic units would have no change, and the wind power generation would have an obvious downward trend from 0:00 to 6:00. In general, the water consumption intensity control could limit the operation of high water consumption equipment to a certain extent and promote the output of clean, renewable, and low water consumption from the equipment. In addition, the purchased electricity amount would increase significantly, especially during peak energy consumption periods. Therefore, water resource consumption control could promote the output from wind and photovoltaic units to a certain extent, and this would decrease the external dependence on power grids to satisfy energy demands.

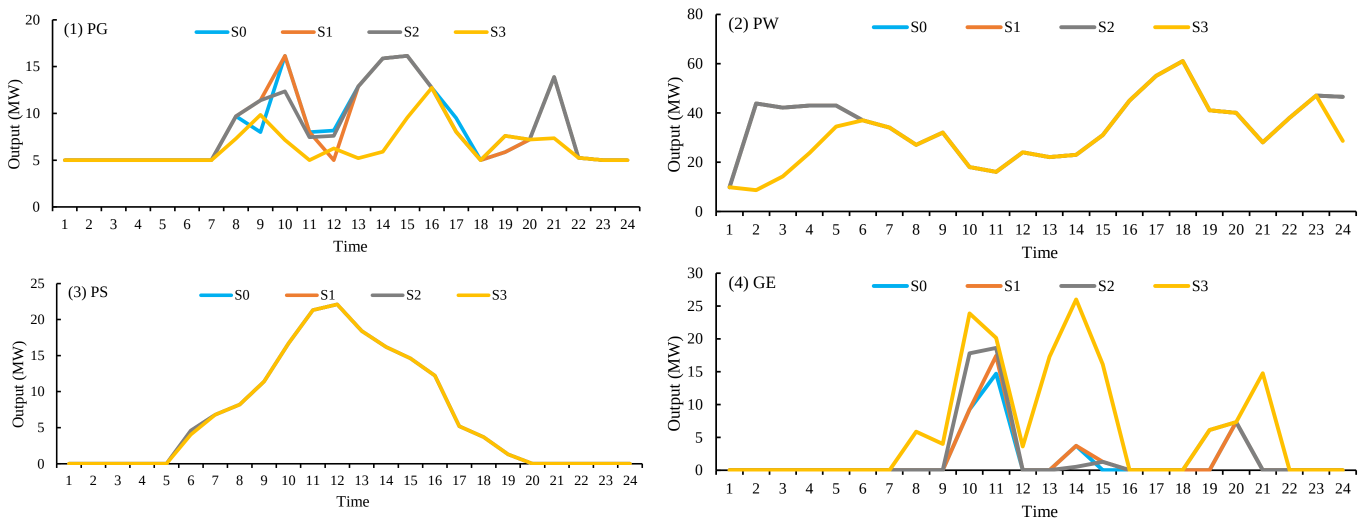

Figure 5. The optimized output of gas turbine (**1**), wind turbine (**2**), photovoltaic unit (**3**), and the purchased power (**4**) amount under different water resource constraints.

Figure 6 shows the energy storage amount in each period under different water consumption control. Overall, as water resource consumption control increases, the operation time and output from energy storage equipment would be gradually reduced. In the S0 scenario (e.g., a normal integrated energy system model), the energy storage would be 10 MW (1:00–9:00 and 18:00–19:00), 2.7 MW (9:00–11:00), 1.25 MW (12:00–15:00), 3.15 MW (17:00–18:00), and 0 for the other times. Furthermore, in the S2 scenario, the highest energy storage value of 10 MW would appear at 2:00–3:00 and 5:00–10:00, and the energy storage during the 11:00–0:00 period would be 0. The energy storage in other periods would also be significantly lower than the S1 and S2 scenarios. Therefore, as the outsourcing power increases, the output from the wind and photovoltaic units would be directly used, and the role of energy storage would also be weakened. From this point, the strategic regulation of power storage reserves would be increased through water consumption control due to stricter constraints surrounding increasing dependence on renewable energy and purchased electricity. Compared with a general energy system model without a water–energy nexus, not only could the control node and key parameters be identified for generating reasonable management schemes, but also, the nexus relationships amongst different parameters could be searched in order to obtain multiple regulating effects, such as water resource consumption control and renewable energy resource utilization.

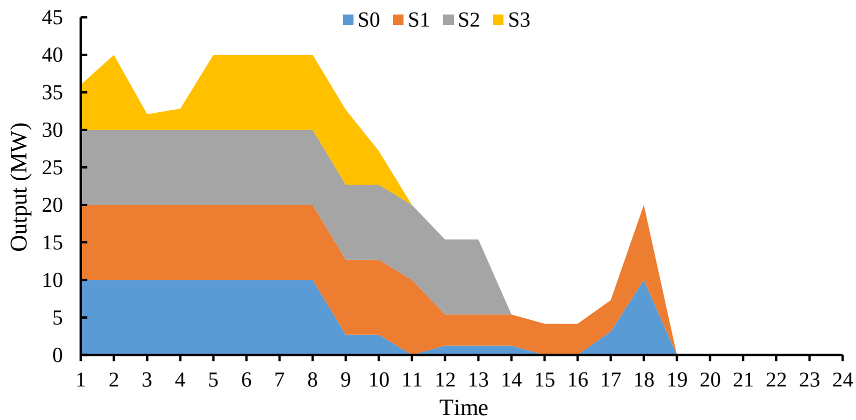

Figure 6. Energy storage amount under different water resource consumption control scenarios.

Table 3 displays the system benefit and water consumption amount under different scenarios. As the intensity of water consumption control increases, the system revenue would show a significant downward trend. The reasons for this would be that the external dependence of the system load would have increased, and more expenses could be used to pay for the cost of electricity purchased. Furthermore, the total water consumption would change a little under the S0, S1, and S2 scenarios, and the consumption amount would be significantly decreased under the S3 scenario. Based on the above analysis, water resource control would be comprehensively considered in an integrated energy system in the same position of the system's external dependence, renewable energy utilization potential, and other factors. The development of more effective control indicators could better promote the effectiveness of bidirectional regulation in the water–energy nexus.

Table 3. System benefits of water consumption amounts under various scenarios.

	Scenario			
	S0	**S1**	**S2**	**S3**
Benefit (10^6 RMB¥)	630.0444	626.4859	618.2493	570.2099
Water amount (m^3)	284.1718	282.7917	282.7916	235.9122

5. Conclusions

Faced with more and more challenges in multiple-resource synergy management in energy systems, an integrated energy system management model was developed for system operation optimization by considering energy–water nexus relationships on an industrial park scale, as shown in this study. Through analyzing the water loss from energy conversion and utilization processes, the energy–water nexus nodes and energy–water nexus effects on the integrated energy system were studied in a typical industrial park for optimization model development. An integrated energy system combined with a CCHP unit, a wind turbine unit, a photovoltaic unit, energy storage equipment, P2G equipment, electric refrigeration, and electric heating technology to satisfy three load demands (cold, heat, and electricity) was considered as a case study. Meanwhile, three water resource consumption control scenarios were designed, and the system operation schemes, the system benefits, and water resource consumption amounts under different scenarios were obtained.

Based on the analysis of these results, it is indicated that: (1) water resource consumption control could effectively promote the utilization of renewable energy and reduce the utilization of traditional units with large water resource dissipation; (2) the role of energy storage would also be weakened as water resource control increases; and (3) the tradeoff amongst a system's external dependence, its income, and its renewable energy utilization potential should all be considered for water resource control, and more effective control indicators could be helpful to promote the effectiveness of water–energy bidirectional regulation in integrated energy systems. In addition, considering carbon emissions control is a key factor for energy system management, water–energy–carbon nexus-oriented integrated energy systems will be a significant area of study in the future.

Author Contributions: Methodology, R.G. and Z.L.; validation, B.Y.; resources, G.H.; data curation, Y.X. (Yanli Xiao); writing—original draft preparation, Y.X. (Yulei Xie); writing—review and editing, R.G. and Z.L.; supervision, Y.X. (Yulei Xie). All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Acknowledgments: We are deeply grateful to the editors and reviewer for his/her insight and careful review.

Conflicts of Interest: The authors declare no conflict of interest.

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