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ARTICLE

Research on Operation of Electrothermal Integrated Energy System Including Heat Pump and Thermal Storage Units Based on Capacity Planning

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ABSTRACT

In view of the Three North areas existing wind power absorption and environment pollution problems, the previous scholars have improved the wind abandon problem by adding electrothermal coupling equipment or optimizing power grid operation. In this paper, an electrothermal integrated energy system including heat pump and thermal storage units was proposed. The scheduling model was based on the load data and the output characteristics of power units, each power unit capacity was programmed without constraints, and the proposed scheduling model was compared with the traditional combined heat and power scheduling model. Results showed that the investment and pollutant discharge of the system was reduced respectively. Wind power was fully absorbed. Compared with the traditional thermal power unit, the proportion of the output was significantly decreased by the proposed model. The proposed system could provide a new prospect for wind power absorption and environment protection.

KEYWORDS

Electrothermal integrated energy system; capacity planning; thermal storage unit; heat pump

1 Introduction

Wind energy, as a clean and pollution-free renewable energy, has highlighted in China due to its economic and environmental potential. The installed capacity of wind turbine in China gradually increases, meanwhile, leads to power abandonment. Reduction of wind abandonment and coal-fired pollutant emission have been a hot research topic of new energy utilization.

In 2019, the new installed wind power capacity was 25.74 million kilowatts, and the national average wind curtailment rate in China was 4% [1]. However, a large amount of the wind power was wasted in the Three North areas, which accounted for 81% of the total wind power abandonment. Due to the "following the thermal load" mode during heating period, the rapid decline of peak load regulation capacity of thermal power plant was regarded as the primary reason for the power curtailment and wind abandonment [2]. In order to meet the demand of heat load in the heating period, the combined heat and power unit operated



in the "following the thermal load" mode. Hence, the adjustable range of power generation output was limited, resulting in a large number of wind abandonment [3,4].

The electrothermal coupling equipment, such as electric boiler or heat pump, are commonly applied in the system to convert the traditional heating mode and decouple the relationship between heat and power. In Dai's work [5], the heat pump was applied in the energy system to avoid waste of renewable energy caused by wind and light, and also reduce conventional energy consumption to achieve environmentally friendly and green power generation. He et al. [6] coupled the combined cooling, heating and power with heat pump, the results showed that the proposed system could solve the energy fluctuation issues. Yu et al. [7] coupled the combined cooling, heating and power with thermal storage unit, the optimized results showed that the absorption of wind power can be improved under the current "following the thermal load" mode. In [8], day-ahead optimal economic scheduling was carried out for the multi-source energy storage micro-grid system containing P2G (Power to Gas), proving that the micro-grid system considering P2G can improve wind Power consumption and reduce system operating cost. A scheduling model including wind power, combined heat and power units and thermal energy storage tanks was established, and the coal saving effects of single combined heat and power unit heating and wind power heating configuration thermal energy storage were compared in [9]. As mentioned in [10], a scheduling model composed with the electrothermal unit, electric boiler and thermal energy storage device was proposed, and the effect of waste air consumption of coordinated heating of electric boiler and thermal energy storage device was analyzed in details. The results showed that the system significantly enhanced the efficiency of heat and power combined heat and power unit operation flexibility. A mathematical model for optimal scheduling of wind power coupled with electric heat pump and gas-fired boiler was established, the results showed that the model effectively improved the utilization efficiency of wind power [11]. Moreover, more and more scholars investigated integrated energy system [12–19]. However, the published literatures generally adopted the electrothermal devices to improve the peak load regulation capacity and wind power accommodation, the variation of the output and capacity of energy supply equipment on the improving the peak shaving capacity and wind power accommodation space of power grid was always ignored.

In this paper, an electrothermal integrated energy system including heat pump and thermal energy storage was proposed at first. Secondly, the model of electrothermal integrated energy system including electric heat pump and thermal energy storage (EIES-EHP&TES) was constructed based on the output characteristics of each unit. Moreover, the EIES-EHP&TES scheduling mode was based on the data load, the capacity of each energy supply unit was planned without constraint. Finally, the proposed scheduling mode was compared with the traditional combined heat and power (CHP) system, and the investment, operation cost and utilization efficiency of wind power were thoroughly investigated. The proposed scheduling mode could reduce the investment and operation cost of the system and improve the utilization efficiency of wind power.

2 Electrothermal Integrated Energy Model Including EHP and TES

The structure diagram of the EIES-EHP&TES is shown in Fig. 1. The system is composed with the power grid and heat pipe network. The electric energy of power grid side is supplied by the wind turbine (WT), thermal power unit (TU) and combined heat and power unit, and the heat provided to consumers is contributed by EHP, TES and CHP.

As shown in Fig. 2, the central heating system is composed of heat source, primary heat supply network, heat exchange station, and secondary heat supply network. However, heat consumers of the central heating system distribute in a large region, which leads to a complex secondary heat supply network. Consequently, heat sources and heat consumers are regarded as the main object of the heating system network model, and

the complex heat supply network is neglected. In each dispatching period, the heat load of consumers refers to the total heat loads of all consumers in the central heating range.



Figure 1: Schematic diagram of electrothermal integrated energy system including EHP and TES



Figure 2: Schematic diagram of central heating system

In the EIES-EHP&TES, the power grid and the heat supply network operate in coordination. The power sources need to meet the power demand of consumers within the dispatch time, in the meantime, they meet the power consumption of EHP unit in the heat supply network. Besides, heat load of the consumers is provided by the CHP, EHP and TES units. The models of wind power, thermal power, CHP, EHP and TES units in the EIES are introduced respectively. Moreover, the power-heat supply and demand balance are established.

2.1 Power Supply System Model

2.1.1 Wind Power Unit

The active power output of wind power unit is mainly determined by the power generated by wind energy. The randomness of wind power production determines the randomness of wind turbine active power output. Fig. 3 shows the wind power output curve of a provincial wind farm. The large-scale integration of wind turbines with random fluctuation characteristics into the grid will greatly affect the safe operation of the power system.



Figure 3: Wind farm output curve of a province

The available wind power output is constrained by the available maximum output of wind turbine:

$$0 \le p_{i,t}^{WP} \le P_{i,t}^{WP} \tag{1}$$

2.1.2 Thermal Power Unit

The power of thermal power units is constrained by its own rated power and climbing [12]:

$$P_{i,\min}^{TP} \le P_{i,t}^{TP} \le P_{i,\max}^{TP}$$
(2)

$$-RD_i^{TP} \cdot \Delta T \le P_{i,t}^{TP} - P_{i,t-1}^{TP} \le RU_i^{TP} \cdot \Delta T$$
(3)

where, $P_{i,t}^{TP}$ is the power of thermal power unit, MW; $P_{i,\min}^{TP}$, $P_{i,\max}^{TP}$ denotes lower and upper limits of output value of thermal power unit, MW, respectively; RD_i^{TP} , RU_i^{TP} separately represents lower and upper limits of output change rate of thermal power unit, MW/h.

2.1.3 Combined Heat and Power Unit

CHP is a mechanical device which can generate electricity and supply heat to users by using steam waste heat of steam turbine generator. Its theoretical efficiency is as high as 85%. The types of CHP are mainly divided into two types: Back pressure steam turbine and extraction condensing steam turbine. The thermoelectric operation characteristics of the two types of units are shown in Fig. 4. The output characteristics of the two types can be expressed simultaneously by Eqs. (4) and (5).

$$P_{i,t}^{CHP} = \alpha_{i,t} \cdot P_i^{CHP} \tag{4}$$

$$Q_{i,t}^{CHP} = \alpha_{i,t} \cdot Q_i^{CHP} \tag{5}$$

where, $P_{i,t}^{CHP}$ means the power of CHP unit, MW; $Q_{i,t}^{CHP}$ is the thermal power of CHP unit, MW; P_i^{CHP} , Q_i^{CHP} implies the rated power and thermal power of CHP unit, MW, respectively; $\alpha_{i,t}$ signifies the output coefficient of combined heat and power unit.



Figure 4: CHP operation characteristics [12]. (a) Back-pressure type, (b) Extraction condensing type

In addition, similar to thermal power unit, the output of combined heat and power unit is constrained by its own rated power and climbing [12]:

$$P_{i,\min}^{CHP} \le P_{i,t}^{CHP} \le P_{i,\max}^{CHP}$$
(6)

$$-RD_{i}^{CHP} \cdot \Delta T \le P_{i,t}^{CHP} - P_{i,t-1}^{CHP} \le RU_{i}^{CHP} \cdot \Delta T$$

$$\tag{7}$$

where, $P_{i,t}^{CHP}$ means the power of CHP unit, MW; $P_{i.min}^{CHP}$, $P_{i.max}^{CHP}$ denotes lower and upper limits of output value of CHP unit, MW, respectively; RD_i^{CHP} , RU_i^{CHP} separately represents lower and upper limits of output change rate of CHP unit, MW/h.

2.2 Heating System Model

2.2.1 Electric Heat Pump

EHP is an efficient energy-saving device which can make full use of low-grade heat energy. The working principle of EHP is shown in Fig. 5. The energy flow is transferred by EHP from low-temperature medium to high-temperature medium. The main components of the heat pump system are compressor, evaporator, heat exchanger and throttle valve. The refrigerant in the compressor is driven by motor to continuously absorb heat from the low-temperature ambient air through the evaporator. Afterward, refrigerant releases heat to the high-temperature environment through heat exchanger.



Figure 5: Schematic diagram of EHP

The heating power of heat pump is shown in Eq. (8):

$$Q_{i,t}^{EHP} = COP \cdot P_{i,t}^{EHP} \tag{8}$$

where, $Q_{i,t}^{EHP}$ is heating power of heat pump, MW; $P_{i,t}^{EHP}$ means power of heat pump, MW; COP denotes energy efficiency coefficient of heat pump.

In addition, the heating power of heat pump should be limited by its own rated heating power:

$$Q_{i,\min}^{EHP} \le Q_{i,t}^{EHP} \le Q_{i,\max}^{EHP}$$
(9)

where, $Q_{i,\min}^{EHP}$, $Q_{i,\max}^{EHP}$ represents lower and upper limits of heating power of heat pump, respectively.

2.2.2 Thermal Energy Storage Device

TES is built on the heat source side of the heating system. The liquid with high specific heat capacity is generally used as the storage medium (such as water, etc.) for short-period storage. According to the works in [8], the daily heat loss of the thermal energy storage device is generally less than 1%. Therefore, the heat loss is neglected in this paper.

The operation of thermal energy storage device is constrained by capacity, thermal power storage and release:

$$S_{i,\min}^{TES} \le S_{i,t}^{TES} \le S_{i,\max}^{TES}$$
(10)

$$0 \le Q_{i,t,c}^{TES} \le Q_{i,c,\max}^{TES} \tag{11}$$

$$0 \le Q_{i,t,f}^{TES} \le Q_{i,f,\max}^{TES} \tag{12}$$

where, $S_{i,t}^{TES}$ represents capacity of thermal energy storage device, MW·h; $S_{i,\min}^{TES}$, $S_{i,\max}^{TES}$ denotes lower and upper limits of capacity of thermal energy storage device, MW·h, separately; $Q_{i,t,c}^{TES}$, $Q_{i,t,f}^{TES}$ means thermal energy storage and release power of thermal energy storage device, MW, respectively; $Q_{i,c,\max}^{TES}$, $Q_{i,f,\max}^{TES}$, Q_{i,f

2.3 Electricity-Heat Supply and Demand Model

2.3.1 Balance of Power Supply

The power system model is established based on DC power flow mode:

$$\sum_{i\in I^{TP}} P_{i,t}^{TP} + \sum_{i\in I^{WP}} P_{i,t}^{WP} + \sum_{i\in I^{CHP}} P_{i,t}^{CHP} = \sum_{i\in I^E} P_{i,t}^{load} + \sum_{i\in I^{EHP}} P_{i,t}^{EHP}$$
(13)

where, P_{it}^{load} means electric load of power users in the system, MW.

2.3.2 Balance of Heat Supply and Demand

The thermal power should meet the heating load demand of heat consumers in the heat supply network:

$$\sum_{i \in I^{H}} Q_{i,t}^{load} = \sum_{i \in I^{CHP}} Q_{i,t}^{CHP} + \sum_{i \in I^{EHP}} Q_{i,t}^{EHP} + \sum_{i \in I^{TES}} Q_{i,t}^{TES}$$
(14)

where, $Q_{i,t}^{load}$ is heating load of heat users in the system, MW.

3 Scheduling Model with EHP and TES Based on Capacity Planning and Its Solution

3.1 Electricity-Heat Supply and Demand Model

The mismatch of load and peak-valley time between power grid and heat supply network leads to the limitation of thermal output of CHP unit in traditional scheduling. It leads to the decline of peak load regulation ability of power grid and the obstruction of wind power grid-connection and absorption further. Therefore, this paper introduces the EHP unit to effectively reduce the output of the CHP unit, and increase the space for the grid to accept wind power. At the same time, TES unit is used to transfer the heat load in different periods, therefore, the CHP unit does not need to keep track of the heat load changes of the heating system during the dispatching period. The EIES-EHP&TES system realizes the unified coordinated planning of electric load and heat load. On the basis of the EIES-EHP&TES system and the unconstrained programming of each energy supply unit, the scheduling mode of the electrothermal integrated energy system is carried out. After the output of each unit is obtained by the CPLEX solver in MATLAB environment, 105% of the maximum output of the thermal power, CHP, EHP and TES units are taken as the rated power and capacity respectively.

The decision variables in the model include wind turbine output power $p_{i,t}^{WP}$, total power of thermal power unit $P_{i,\max}^{TP}$, total power of CHP unit $P_{i,\max}^{CHP}$, total power of heat pump unit $Q_{i,\max}^{EHP}$ and total capacity of thermal energy storage device $S_{i,\max}^{TES}$.

3.2 Objective Function

The objective of the model is to schedule the output of each unit reasonably while satisfying the operation conditions of the integrated electrothermal energy system, so as to minimize the cost of power generation and heating. In other words, the total coal consumption of the whole electrothermal integrated energy system reaches the minimum:

$$\min C = \sum_{t=1}^{I} \left(\sum_{i \in I^{TP}} C_{i,t}^{TP} + \sum_{i \in I^{CHP}} C_{i,t}^{CHP} \right)$$
(15)

$$C_{i,t}^{TP} = \mu^{TP} \cdot P_{i,t}^{TP} \tag{16}$$

$$C_{i,t}^{CHP} = \mu_P^{CHP} \cdot P_{i,t}^{CHP} + \mu_Q^{CHP} \cdot Q_{i,t}^{CHP}$$

$$\tag{17}$$

where, $C_{i,t}^{TP}$, $C_{i,t}^{CHP}$ separately means operation cost of thermal power unit and CHP unit, \$; μ^{TP} denotes conversion coefficient of standard coal for power supply of thermal power unit; μ_{P}^{CHP} , μ_{Q}^{CHP} indicates conversion coefficient of standard coal for power and heating supply of CHP unit, independently.

The system constraints are composed of Eqs. (1)–(12) of the above components, Eqs. (13) and (14) for the system power-heat supply and demand balance conditions.

3.3 Solution Method and Process

From the above, the capacity scheduling process of the EIEC-EHP&TES can be interpreted as: The total coal consumption of the system is minimized under the constraints of the grid current, the wind power plant generation, heat pump heat-to-electric ratio, thermal energy storage and release rate, the supply and demand balance of the heating system, etc. The scheduling model is described as follows:

$$\min C = \sum_{t=1}^{T} \left(\sum_{i \in I^{TP}} \left(\mu^{TP} \cdot P_{i,t}^{TP} \right) + \sum_{i \in I^{CHP}} \left(\mu_{P}^{CHP} \cdot P_{i,t}^{CHP} + \mu_{Q}^{CHP} \cdot Q_{i,t}^{CHP} \right) \right)$$
(18)

$$s.t \begin{cases} \sum_{i \in I^{TP}} P_{i,t}^{TP} + \sum_{i \in I^{WP}} P_{i,t}^{WP} + \sum_{i \in I^{CHP}} P_{i,t}^{CHP} = \\ \sum_{i \in I^{E}} P_{i,t}^{load} + \sum_{i \in I^{CHP}} Q_{i,t}^{EHP} + \\ \sum_{i \in I^{TES}} Q_{i,t}^{TES} Q_{i,t}^{TES} \\ 0 \le p_{i,t}^{WP} \le P_{i,t}^{WP} \\ -RD_{i}^{TP} \cdot \Delta T \le P_{i,t}^{TP} - P_{i,t-1}^{TP} \le RU_{i}^{TP} \cdot \Delta T \\ -RD_{i}^{CHP} \cdot \Delta T \le P_{i,t}^{CHP} - P_{i,t-1}^{CHP} \le RU_{i}^{CHP} \cdot \Delta T \\ Q_{i,t}^{EHP} = COP \cdot P_{i,t}^{EHP} \\ 0 \le Q_{i,t,c}^{TES} \le Q_{i,c,\max}^{TES} \\ 0 \le Q_{i,t,f}^{TES} \le Q_{i,f,\max}^{TES} \end{cases}$$

$$(19)$$

Eqs. (18) and (19) constitute a typical mixed integer nonlinear programming problem with inequality constraints. After transforming the nonlinear constraints into linear constraints, the problem can be solved by CPLEX solver in MATLAB environment.

4 Validation

The EIES scheduling mode is compared with the traditional mode in terms of wind power consumption, investment and operation cost (system coal consumption). Afterward, the thermal energy storage device is introduced to analyze the impact of the thermal energy storage on the EIES scheduling mode. Therefore, the three modes are described as follows:

- 1. Mode 1. The traditional CHP scheduling mode with EHP is to reasonably schedule the output of power generation and heating components within the range of specialized capacity of thermal power, CHP and heat pump units. It represents the current operation mode of most integrated energy system.
- 2. Mode 2. The EIES scheduling mode with EHP based on capacity scheduling, which does not limit the output of thermal power, CHP and EHP units. When the load data is given and according to the output characteristics of each component, the output of each generation and heating component is reasonably scheduled. Then 105% of the maximum outputs of thermal power, CHP and EHP units are taken as rated power value respectively.
- 3. Mode 3. The EIES scheduling mode with EHP and TES based on capacity scheduling, which does not limit the output of thermal power, CHP, EHP and TES units. When the load data is given and according to the output characteristics of each component, the output of each generation and heating component is reasonably scheduled. Then 105% of the maximum outputs of thermal power unit, CHP, EHP and TES units are taken as rated power and capacity value separately.

4.1 Data of Test System

The daily electric load, heat load and wind power curves shown in Fig. 6 are selected as typical data in winter for analysis and calculation. Tab. 1 shows the rated power of each component in Mode 1 [11].

4.2 Result Analysis

4.2.1 Performance Comparison of Models

The optimal solutions of the three scheduling modes are carried out according to the data of daily electric load, heat load and wind power given in Section 3.1. The output curves of each unit under different scheduling modes are drew in Figs. 7-12. After the introduction of EHP unit in the heating system, Mode 1 can relieve the energy supply mode "Following the thermal load" of CHP unit in a certain extent.

In the peak period of heating, EHP unit will replace part of the heat load borne by the CHP unit, reduce the power output of the CHP unit, release the capacity of the power system to accept wind power, and reduce the abandoned wind power in system. As indicated in Fig. 7, excess electricity will be generated due to the output limits of conventional energy supply units (thermal power unit, CHP unit) and EHP unit, which needs to be fed back to the external power grid. As displayed in Fig. 10, EHP works at the maximum load most of the time, so the reliability of the EHP will be greatly challenged, and the system will generate wind abandonment. The abandoned wind reaches 14.07% in Mode 1 as demonstrated in Fig. 13.



Figure 6: Typical daily electric load, heating load and wind power output in winter

Table 1. Operation parameters of each unit in traditional scheduling in	iouc
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Parameters	ТР	WP	CHP	EHP
Number of units	1	1	2	2
Minimum power/MW	0	0	0.5	0
Maximum power/MW	12	5	6	3
Ramp constraints/MW	4		1.5	
Efficiency	0.95	0.95	0.85	0.99
$\mu/kg.kWh^{-1}$	0.4	_	$\mu_O^{CHP} = 0.11$	
			$\mu_P^{\rm CHP} = 0.38$	



Figure 7: Mode 1 power output of each unit



Figure 8: Mode 2 power output of each unit







Figure 10: Mode 1 heat output of each unit



Figure 11: Mode 2 heat output of each unit



Figure 12: Mode 3 heat output of each unit



Figure 13: Mode 1 wind power usage

In Mode 2, while daily power load and heat load are given, the outputs of each energy supply unit are reasonably scheduled. As revealed in Fig. 8, the system can realize the internal balance between power supply and consumption without generating excess electricity. It can be seen from Fig. 11 that the output of heat pump increases after the limitations of rated power are removed, and the abandoned wind in

Mode 1 from 23:00 to the next 6:00 is absorbed, so as to realize 100% wind power consumption of the whole system. Mode 3 introduces TES unit on the basis of Mode 2. As demonstrated in Figs. 9 and 12, the electric and heat outputs of the EIES-EHP&TES become smoother compared with the original demand of daily electric load and heat load, so as to realize the "peak shaving and valley filling" of heat and electric load, and improve the flexibility of the system.

4.2.2 Economic Comparison of Models

Tab. 2 demonstrates the comparison of output or capacity scheduling of each unit in the three modes. The output value of each unit in Mode 1 has been set before calculation. The output or capacity scheduling values of each unit in Mode 2 and Mode 3 are the sum of the maximum and standby output. By means of the initial investment cost of each component given in Tab. 3, the investment cost of each mode can be calculated.

TP/MW CHP/MW EHP/MW Thermal energy storage device/MW·h

Table 2: Capacity planning of each unit under three modes

	== / = / = / /			
1	12	12	6	_
2	2.7	11.9	10.1	
3	0	12.8	9.5	26.7

 Table 3: Initial investment of each component

	TP	CHP	EHP	Thermal energy storage device
Construction cost (ten thousand yuan/MW)	480	680	220	20

Tab. 4 indicates the comparison of wind power utilization, operation cost and investment in the three modes. The complete absorption of wind power is realized in Mode 2 and Mode 3, which leads to the use of primary energy (coal and natural gas) in the electric-heating integrated energy system is reduced. Therefore, the total coal consumption of system has decreased compared with Mode 1. In Mode 3, the TES unit stores the additional thermal output generated by EHP and CHP, while the heat load is low. Besides, TES releases the heat to consumers during the peak period of heating, which further reduces the heat output of CHP. Thus, the coal consumption of the system compared with Mode 2 is reduced, which correspondingly improves the environmental performance of the whole system. Compared with Mode 1, Mode 2 reasonably schedules the capacities of each energy supply unit by means of reducing the capacity of thermal power unit and increasing the capacity of heat pump unit. The construction cost of thermal power unit is higher than that of heat pump unit, so the investment is reduced by 23.8%. In Mode 3, because of the introduction of TES unit, the electric output and heat output of the system become smoother, and thermal power unit is not required. Therefore, the thermal power unit is directly subtracted, meanwhile, the increased capacities of EHP unit and TES unit are relatively low. The investment cost is reduced by 26.0% compared with Mode 1, which improves the economic performance of the whole electrothermal integrated energy system.

	Mode 1	Mode 2	Mode 3
Wind power utilization	85.93%	100%	100%
System coal consumption/kg	104338	96323	95770
Investment cost/ten thousand yuan	15240	11610	11272
Cost saving rate		23.8%	26.0%

Table 4: Wind power utilization, operation cost and investment under three modes

5 Conclusions

In view of the limitation of wind power consumption and grid scheduling capacity, an EIES-EHP&TES system is constructed, the scheduling mode based on capacity scheduling is proposed, and the scheduling mode is compared with the traditional CHP scheduling mode with EHP, the influence of TES to the EIES scheduling mode based on capacity scheduling is analyzed. The conclusions are as follows:

- 1. Compared with the traditional CHP scheduling mode with EHP, the EIES scheduling mode with EHP based on capacity scheduling solves the problem of regulation space caused by the output of traditional equipment and the insufficient capacity scheduling of EHP in heating period. At the same time, the proposed scheduling mode can effectively promote the utilization of wind power energy in heating period, the wind power is 100% consumed;
- 2. The EIES scheduling mode based on capacity scheduling can improve the economic, environmental and reliable performance of the whole system. System coal consumption is decreased by 8.22%, and all power supply units are not demanded to work at maximum power for a long time;
- 3. The introduction of TES unit in the EIES system can further decouple the strong mutual relationship between heat and power caused by the traditional power generation method of CHP, strengthen the coordination ability between power and heating system, and further increase the economic advantages of the EIES system. The investment saving rate is 26.0%.

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Conflicts of Interest: We declare that we have no conflicts of interest to report regarding the present study.

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