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An Optimal Dispatching Model for Integrated Energy Microgrid Considering the Reliability Principal–Agent Contract

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Abstract: As the increasing penetration of sustainable energy brings risks and opportunities for energy system reliability, at the same time, considering the multi-dimensional differentiation of users' reliability demands can further explore the potential value of reliability resources in Integrated Energy Microgrid (IEM). To activate the reliability resources in a market-oriented perspective and flexibly optimize the operational reservation in dispatch, an optimal dispatching model in IEM considering reliability principal–agent contracts is proposed. We establish the reliability principal–agent mechanism and propose a cooperative gaming model of Integrated Energy Operator (IEO) and Integrated Energy User (IEU) based on the optimal dispatching model. At the upper level, the economic dispatching model of IEO is established to optimize the operation reservation, and the reliability principal–agent contract from users in the lower level would influence reliability improvement. Each IEU in the lower level maximizes its energy utilization and gives the corresponding reliability principal–agent incentives according to the reliability improvement degree and its actual demand. The bi-level model is solved by the KKT condition and strong duality theorem. A case study verifies the effectiveness of the proposed model in reducing the energy dispatch cost, improving the economic benefits of each participant, realizing the optimal allocation of reliability resources and optimizing the IEM energy structure, and the sensitivity analysis of dispatch cost with the user's energy-using benefits is discussed.

Keywords: optimal dispatching model; reliability principal-agent contract; cooperative gaming; bi-level optimization

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1. Introduction

With distributed energy developing rapidly, the higher penetration of renewable energy is a double-edged sword for energy system reliability [1] and energy supply flexibility [2], and in this context, with the Integrated Energy Microgrid (IEM) flourishing, the traditional units [3] and the auxiliary service energy market is experienced a great change within their footprint [4]. Therefore, in this context, the energy dispatching optimization in IEM considering the market mechanism of customer reliability auxiliary services can not only effectively explore the potential benefits of reliability in energy dispatching, but also allocate the reliability resources fairly and reasonably according to the differentiated market demand; thus, it can further improve the economic benefits of energy use for the whole of society, and promote energy structure transformation.

With the diversification of the energy market, energy reliability is gradually transforming from a public product to a private product as an auxiliary service [5]. Therefore, the traditional vertical administrative energy reliability management needs to be changed and updated. As the demand differentiation for users' energy reliability, reliability services should also consider the interests of both the system-side and user-side to achieve a win–win result. In articles [6–8], based on the idea of "the higher quality, the higher price", the reliability improvement cost is evaluated and priced from an economic view for reliability services. Article [6] indicates that the pricing signal is sensitive to network reliability, article [7] develops an analytical "electricity price reliability" model considering the time of use (TOU) strategy to evaluate the reliability of the power system, a new method of reliability pricing is proposed to reflect the value of energy storage systems on consumer-centric reliability improvement in article [8]. Furthermore, with the increasing penetration of sustainable energy, the operational risk of energy operators will continue to increase, which impacts negatively the revenue of integrated energy market participants and increases system costs. Consequently, by establishing a market-based approach for setting user reliability preference [5], energy operators can recover their costs in the integrated energy systems with photovoltaic uncertainty and system networks [9]. In addition, as the transaction model for reliability indexes such as the system average interruption duration index (SAIDI), system average interruption frequency index (SAIFI), customer average interruption duration index (CAIDI), customer average interruption frequency index (CAIFI) and loss of load probability (LOLP) is commonly adopted [10], and the transaction depends on customer damage function (CDF) [11] and service quality [12] is also widely used nowadays, it is a good method to establish a reliability service mechanism with risk management tools [10,12]. By introducing an insurance mechanism, new blood is injected into the reliability management field by enhancing the economic incentives for reliability improving decisions with excellent economics [13] and controlling distributed energy resources [14], energy storage systems [15]. However, since the goal of the insurance mechanism is to spread the uncertainty risk of the user's lost load loss, it doesn't fully exploit the potential benefits of the reliability resource optimal allocation. Meanwhile, although these studies have effectively improved the energy system reliability through various market mechanisms, most of the proposed models are still from a long-term perspective by changing the grid structure, etc., and do not meet the dynamically changing reliability needs of users in real-time and with a flexible manner.

In the real-time dispatching of IEM, the reliability improvement mainly relies on the optimization of operational reservation. Unlike the traditional system, the IEM considers the reservation co-optimization among multiple-energy systems, promotes renewable energy consumption, and ensures system reliability [16]. With the increase in uncertainties in the energy system, article [17] presents a stochastic mathematical framework to address epistemic uncertainty and aleatory uncertainty, which reduces the risk caused by uncertainty effectively. As for the uncertainties of equipment failures and load changes, considering the uncertainty of unit output, article [18] defined the safety constraints of IEM operation, and established a stochastic optimization dispatching model, which improved the system reliability effectively. Article [19] introduced the conditional value at risk theory into the risk quantification of IEM and built a robust optimization model for day-ahead dispatching. For the multiple failures of system components, probabilistic reliability constraints are introduced in the reservation dispatching optimization model. By introducing chance constraints of multiple reliability indicators [20], component capacity [21], and dynamic operational reliability constraints [22] in day-ahead dispatching, reservation optimization is performed to improve system reliability. However, most studies have focused on solving uncertainties from system perspectives to improve energy supply reliability, ignoring the strong subjective initiative and the great potential value of users for reliability improvement. Therefore, considering users' energy reliability demand and their variability will bring more improvement space for IEM dispatching in balancing economy and reliability.

To address the above problems, based on the differentiation of users' energy reliability demand, we propose an optimal dispatching model for IEM considering a reliability principal–agent contract, to find a balance between the economy and reliability of IEM dispatching by market tools. This paper establishes the reliability principal–agent mechanism and proposes a cooperative gaming model of Integrated Energy Operator (IEO) and Integrated Energy User (IEU) based on the optimal dispatching model. At the upper level, the economic dispatching model of IEO is established to optimize the operation reservation, and the reliability principal–agent contract from users in lower-level is influencing the degree of reliability improvement. Each IEU in the lower level maximizes its energy utilization and gives the corresponding reliability principal–agent incentives according to the degree of reliability improvement and its actual demand. The bi-level model is solved by the KKT condition and strong duality theorem. A case study verifies the effectiveness of the proposed model in reducing the energy dispatch cost, improving the economic benefits of each participant, realizing the optimal allocation of reliability resources and optimizing the IEM energy structure, and the sensitivity analysis of dispatch cost with user's energy use benefits is discussed.

2. Energy Reliability Principal-Agent Model

An IEM has a variety of designs and sizes, and typically contains one or more kinds of distributed energy as shown in Figure 1, such as wind turbine (WT), photovoltaic (PT), micro combined heat and power (CHP) system, etc., and multi-energy loads, such as electrical and thermal loads, with various characteristics. In these structures, the integration and coordination of various energy systems can provide a good accommodation environment for distributed renewable energies and good performance in energy efficiency, and reliability. Due to the subtlety of the energy micro-grid, it can not only realize lean and high-quality improvement on energy services, but also adapt to the rules of energy marketization, which makes it a good choice as a pilot for energy market reform.

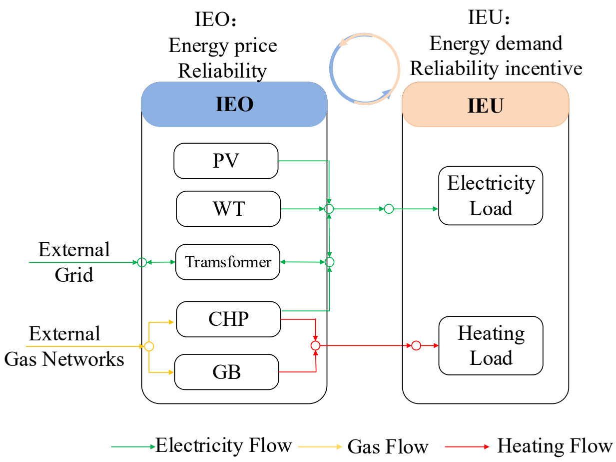

Figure 1. The energy frameworks of IEM.

With the increasing uncertain factors in energy dispatching, energy reliability is facing new opportunities and challenges for both systems operators and users; as the energy auxiliary market is developing into diversified and individualized areas, considering users' reliability demand differentiation in the energy reliability resources allocation optimization would have a strong market value and potential to lead the trend.

The principal–agent relationship refers to one or more participants appointing another participant to serve a certain business according to an explicit or implicit contract, and paying them corresponding remuneration according to the quantity and quality of provided services. The establishment of the new principal–agent relationship is a supplement and improvement of the traditional relationship between operators and users. In addition, in the market context, we focus on quantifying the load loss with economic indicators. Therefore, with the traditional LOLP conception applied in calculating users' energy shortage probability, it is more convenient to quantify the load loss for an economic expected value by selecting a probability. In addition, when a detailed shortage time index is needed, and multiplication with a detailed time scale is carried out, the average outage time per hour can also be obtained easily.

According to the principal–agent theory, in the IEM, the energy reliability principal-agent model consists of the principal IEU and the agent IEO. With the quantity and quality of reliability improvement provided by IEO, IEU gives IEO the corresponding remuneration under this principal–agent mechanism. The model makes the reliability resource allocation further improved by highlighting users' participation, and follows the direction of energy market development. With the effective economic incentive from users, it not only keeps the balance between the reliability improvement degree and the economy of its cost in energy dispatching, but also flexibly satisfies the diversification of users' reliability demands in the spatial and temporal dimensions.

2.1. Reliability Principal-Agent Function

Since the energy supply interruption will lead to different damage degrees to the user's energy-using utilization during their business hours, from the perspective of the user's loss of load probability (LOLP), the user's energy-using utilization considering the energy reliability index LOLP in a short dispatching period is as follows.

$$U_{\mathrm{IEU}i} = \sum_{t=1}^{T} \sum_{\mathrm{x} \in \mathrm{X}} (1 - LOLP_{i,t}^{\mathrm{x}}) b_{i,t}^{\mathrm{x}} \tag{1}$$

where, T is the dispatching period (unit: hour), X is the energy type, which contains electricity and heating, that is $\mathrm{X} = \{x | x \in (\mathrm{e}, \mathrm{h})\}$; $U_{\mathrm{IEU}i}$ is the energy-using utilization (unit: USD) of the user i; $LOLP_{i,t}^{\mathrm{x}}$ is its loss of load probability, which also represents the reliability level; and b_i^{x} is the benefits (unit: USD) that the user earns without energy supply interruption.

According to the principal-agent theory, the amount of incentive payoff is directly related to the benefits that users gain with the reliability improvement. Therefore, based on the actual benefits-improved for users by reliability improvement, the setting of the reliability principal-agent contact is expressed as follows.

$$\Delta U_{i,t}^{x,rel} = (\widehat{LOLP}_{i,t}^{x} - LOLP_{i,t}^{x}) b_{i,t}^{x} \tag{2}$$

$$I_{\mathrm{rel},i,t}^{x} = \alpha_{i,t}^{x} + \beta_{i,t}^{x} (\widehat{LOLP}_{i,t}^{x} - LOLP_{i,t}^{x}) b_{i,t}^{x} \tag{3}$$

where, $\Delta U_{i,t}^{x,rel}$ is the additional energy-using utilization (unit: USD) that is brought by reliability improvement; $I_{\mathrm{rel},i,t}^{x}$ is the reliability incentive (unit: USD) that principal-agents contact defined, $\alpha_{i,t}^{x}$ is fixed incentive (unit: USD) paid to the IEO; and $\beta_{i,t}^{x}$ is the incentive coefficient, which represents the importance of energy supply at that moment; it would be influenced by the business benefits, reliability situation, energy pricing and so on.

2.2. Reliability Principal-Agent Constraint

To maintain the fairness of the principal–agent contract, we stipulate that, on one hand, as shown in Equation (6), when the user does not choose a reliability principal–agent contract, the IEO must maintain at least the original reliability during the period, and cannot maliciously change the reliability index to cheat the user of the reliability incentive out of their pay; on the other hand, as shown in Equation (7), when the amount of the reliability incentive proposed by the user is less than the cost paid by the IEO to improve the energy reliability in dispatching, the IEO has the right to reject the contract and maintain energy reliability in the original state.

$$\alpha_{i,t}^{x} \geq 0 \tag{4}$$

$$0 \leq \beta_{i,t}^{x} \leq 1 \tag{5}$$

$$\widehat{LOLP}_{i,t}^{x} - LOLP_{i,t}^{x} \geq 0 \tag{6}$$

$$I_{\mathrm{rel},i,t}^{x} \geq C_{i,t}^{\mathrm{x,rel}} \tag{7}$$

where, $C_i^{x,\mathrm{rel}}$ is the reliability improving cost (unit: USD) by IEO, which can be obtained after IEO energy dispatching.

3. IEM Optimal Dispatching Model Considering Reliability Principal-Agent Contact

3.1. Objective

According to the reliability principal-agent model proposed above, IEO takes its net revenue R_{IEO} maximum as the dispatching optimization objective, and the relevant factors include the revenue of energy selling to IEU $R^x_{\mathrm{sell},i,t}$, the incentive obtained from the reliability principal-agent contract $I^x_{\mathrm{rel},i,t}$, the operation and maintenance cost of the units under normal operation scenarios $C^x_{\mathrm{N},y,t}$, and the reservation purchase cost under each failure scenario $C^x_{s,y,t}$. The objective function can be described as follows.

$$\begin{aligned}\max R_{\mathrm{IEO}} = \sum_{t=1}^{T} \sum_{x\in \mathrm{X}} [\sum_{i=1}^{N} (R^x_{\mathrm{sell},i,t} + I^x_{\mathrm{rel},i,t}) \\ - \sum_{y\in \mathrm{Y}^{\mathrm{x}}} (C^x_{\mathrm{N},y,t} + C^x_{s,y,t})]\end{aligned} \tag{8}$$

where, Y^{x} is the set of equipment generating energy x, $\mathrm{Y}^{\mathrm{x}} = \{\mathrm{Y}^{\mathrm{e}}, \mathrm{Y}^{\mathrm{h}}\}$, and the electricity part includes combined heat and power (CHP), external grid (EG), wind turbine (WT) and photovoltaic(PV), $\mathrm{Y}^{\mathrm{e}} = \{y|y \in (\mathrm{CHP}, \mathrm{EG}, \mathrm{WT}, \mathrm{PV})\}$; and the heating part includes combined heat and power (CHP), external heating networks (EH) and a gas boiler (GB), $\mathrm{Y}^{\mathrm{h}} = \{y|y \in (\mathrm{CHP}, \mathrm{EH}, \mathrm{GB})\}$.

$$R^x_{\mathrm{sell},i,t} = \omega^x_t L^x_{i,t} \Delta t \tag{9}$$

$$C^x_{\mathrm{N},y,t} = c^{x,\mathrm{p}}_{y,t} P^x_{y,t} \Delta t \tag{10}$$

$$C^x_{s,y,t} = \sum_{s\in S} p_{t,s} c^{x,\mathrm{r}}_{y,t} R^x_{y,t,s} \Delta t \tag{11}$$

$$c^{x,\mathrm{r}}_{y,t} = \omega^{x,\mathrm{p}}_{\mathrm{EG/EH},t} - c^{x,\mathrm{p}}_{\mathrm{y},t} \tag{12}$$

where, ω^x_t is the selling price (unit: USD) for IEU, $L^x_{i,t}$ is the load (unit: kWh) of the user i; $c^{x,\mathrm{p}}_{y,t}$ is the production cost (unit: USD) of equipment y supplying energy x at time t, and $P^x_{y,t}$ is corresponding unit output (unit: kW) according to the optimal dispatching in the normal state; S is a set of failure scenes, $s \in S$, $p_{t,s}$ is the probability of failure scene s, $c^{x,\mathrm{r}}_{y,t}$ is the reverse cost (unit: USD) of equipment y, which is the difference of the external market selling price $\omega^{x,\mathrm{p}}_{\mathrm{EG/EH},t}$ and $c^{x,\mathrm{p}}_{y,t}$, $R^x_{y,t,s}$ is the corresponding reserve amount (unit: kWh) that dispatches in failure scene s.

3.2. Energy Dispatching Constraints

3.2.1. Economic Constraints

To maintain the energy market order in the IEM, the apportionment mechanism of reliability improving cost should obey the rule of "More money out, more money in", which is shown as followed.

$$C^{x,\mathrm{rel}}_t = \sum_{y\in \mathrm{Y}^{\mathrm{x}}} C^x_{s,y,t} \tag{13}$$

$$C^{x,\mathrm{rel}}_{i,t} = \frac{\Delta U^{x,\mathrm{rel}}_{i,t}}{\sum_{i=1}^{N} \Delta U^{x,\mathrm{rel}}_{i,t}} C^{x,\mathrm{rel}}_t \tag{14}$$

where, $C^{x,\mathrm{rel}}_t$ is the reliability improving cost (unit: USD) by IEO, $C^{x,\mathrm{rel}}_{i,t}$ is the reliability improving cost (unit: USD) apportioned to each user, which is according to their additional energy utilization $\Delta U^{x,\mathrm{rel}}_{i,t}$.

3.2.2. Operational Constraints for Normal State

- Energy balance constraint

$$\sum_{i=1}^{N} L_{i,t}^{x} = \sum_{y \in Y^{x}} P_{y,t}^{x} \tag{15}$$

- Multi energy supply constraints

$$u_{y,t}^{p} P_{y,t,\min}^{x} \leq P_{y,t}^{x} \leq u_{y,t}^{p} P_{y,t,\max}^{x} \tag{16}$$

$$\Delta P_{y,\max}^{\text{low}} \leq P_{y,t}^{x} - P_{y,t-1}^{x} \leq \Delta P_{y,\max}^{\text{up}} \tag{17}$$

where, $u_{y,t}^{p}$ is the available status of equipment y over period t, 1 for on, 0 for off. $P_{y,t,\min}^{x}$ and $P_{y,t,\max}^{x}$ is the upper and lower bounds of the output (unit: kW) of energy x from equipment y, respectively; $\Delta P_{y,\max}^{\text{low}}$ and $\Delta P_{y,\max}^{\text{up}}$ is the maximum ramp rate of reducing and increasing output (unit: kW/h) of equipment y, respectively.

As for the multi-energy units, their energy conversion functions for CHP and GB are as follows.

$$P_{\text{CHP},t}^{\text{e}} = \eta_{\text{CHP}}^{\text{g2e}} P_{\text{CHP},t}^{\text{g}} \tag{18}$$

$$P_{\text{CHP},t}^{\text{h}} = \gamma_{\text{CHP}}^{\text{e2h}} \eta_{\text{CHP}}^{\text{g2e}} P_{\text{CHP},t}^{\text{g}} \tag{19}$$

$$P_{\text{GB},t}^{\text{h}} = \eta_{\text{GB}}^{\text{g2h}} P_{\text{GB},t}^{\text{g}} \tag{20}$$

where, $\eta_{\text{CHP}}^{\text{g2e}}$ is the electricity generating efficiency of CHP, and $\eta_{\text{GB}}^{\text{g2e}}$ is the heating generating efficiency of GB, respectively; $\gamma_{\text{e2h}}^{\text{CHP}}$ is the thermal power ratio of CHP.

3.3. Energy Reliability Model

3.3.1. Component State Probability

In this model, the reliability index of the IEM is defined by the LOLP of the power supply system and the heating system, and obtaining them by transforming the reliability assessment model into a reliability probability constraint in energy dispatching. A two-state component reliability model is adopted, and its state transfer process is considered as a homogeneous Markov process. The dispatching cycle is divided into 24 intervals, and each component is in normal operation before the first interval; consequently, a component may have 224 state sequences, from which the normal and fault probability of each component at each period can be obtained. Considering the first-order faults and the IEM-containing S components, the probabilities of sth system state and the $(s+1)$th (normal) system state can be found as follows, respectively.

$$p_{t,s} = p_{t,s}^{1} \prod_{k,k \neq s}^{S} p_{t,k}^{0} \tag{21}$$

$$p_{t,s+1} = \prod_{s=1}^{S} p_{t,s}^{0} \tag{22}$$

where, $p_{t,s}^{0}$ and $p_{t,s}^{1}$ is the probability of component s being in working and fault states at time interval t.

$$u_{y,t,s} P_{y,\min} \leq P_{y,t}^{x} + R_{y,t,s}^{x} \leq u_{y,t,s} P_{y,\max} \tag{23}$$

where, $u_{y,t,s}^{x}$ is the state of equipment y supplying energy x in the state scenario s during the time interval t, and 1 for normal operation, 0 for fault.

3.3.2. Energy System Reliability Assessment

When there is a shortage of a certain energy supply in the IEM, the amount of its optimal load shedding to different users under the scenario s is $LOSS^x_{i,t,s}$, and it keeps the energy supply–demand balance after the load cut, as shown in Equation (24). And Equation (25) represents the constraint on the energy cut amount according to the user reliability demand. Finally, the energy interruption situation of each user under multiple scenarios is counted to calculate the LOLP index, which would be regarded as an important index in the cooperative game to influence the optimal dispatching of IEM.

$$\sum_{i=1}^{N}(L^x_{i,t} - LOSS^x_{i,t,s}) = \sum_{y \in Y^x} u^x_{y,t,s}(P^x_{y,t} + R^x_{y,t,s}) \tag{24}$$

$$0 \le LOSS^x_{i,t,s} \le u^{x,loss}_{i,t,s,up} L^x_{i,t} \tag{25}$$

$$LOLP^x_{i,t} = \sum_{s \in S} p_{s,t} u^{x,loss}_{i,t,s,up} \tag{26}$$

where, $LOSS^x_{i,t,s}$ is the load loss amount (unit: kWh) for each energy system under scene s; $u^{x,loss}_{i,t,s,up}$ is the load loss state; when it is 0, it means no load loss, and 1 means load loss.

4. Bi-Level Cooperative Gaming Model

4.1. User-Side Model in the Lower Level

According to the analysis of the relationship between the user's energy utilization and the reliability improvement in Chapter II, the user's business revenue with the reliability resource optimization is $(1 - LOLP^{x}_{i,t})c^{x,\mathrm{beni}}_i$. After considering the basic energy sale and the paid-for reliability principal–agent contract, the user's objective function to maximize the overall energy utilization is as follows.

$$I^x_{\mathrm{rel},i,t} = \alpha^x_{i,t} + \beta^x_{i,t}(\widehat{LOLP}^x_{i,t} - LOLP^x_{i,t})b^x_{i,t} \tag{27}$$

The participation constraints in the game are described as Equations (4)–(7) in Chapter II.

4.2. Frameworks of Cooperative Gaming

Based on the energy dispatch and reliability principal-agent mechanism in the IEM, the game participants are motivated by the common interest direction of improving the reliability of system operation. Since the objective of the gaming is the same, and the information of the reliability transaction is symmetrical, the game is a cooperative game and can achieve the Pareto optimum under this gaming information environment. The cooperative game emphasizes collective rationality, and the core problem is how to cooperate and allocate the benefits gained from it. Therefore, in the proposed model, the gaming focuses on the allocation of the system reliability resources based on the reliability principal–agent contract, and it is also played to maximize the profit of each party.

As shown in Figure 2, in the bi-level cooperative game, the upper-level subject is the Integrated Energy Operator, IEO, and the lower-level subject is each Integrated Energy User who is integrated by the principal–agent contract, IEU.

At the upper level, the IEO will purchase and dispatch energy operative reservations according to the reliability demand within the IEM, achieve a balance between the stable and reliable energy supply and the economic dispatch, and coordinate resources flexibly to meet the demand of multiple energy loads, and finally gain from the reduction of dispatch energy costs, energy sales, and auxiliary services of improving reliability. Its specific contents include regulating energy prices, negotiating reliability principal–agency contracts, deciding on whether to accept reliability service contacts or not, and allocating reliability resources.

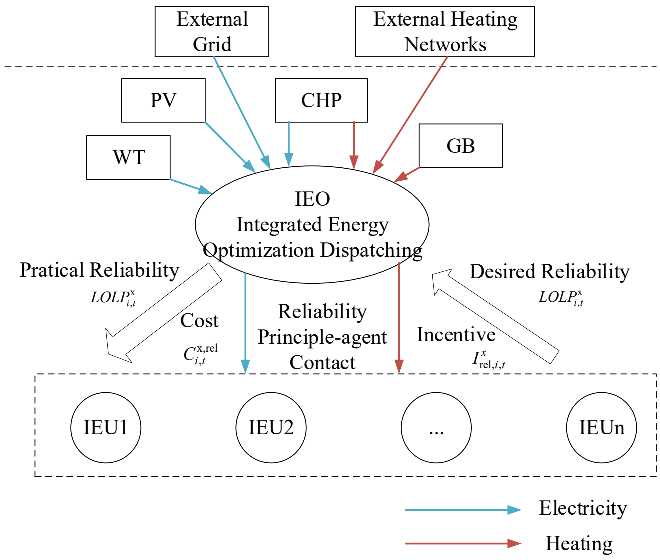

Figure 2. The frameworks of cooperative gaming with energy flow.

At the lower level, users optimize their energy reliability demand strategies based on the reliability information and energy price information transmitted from the upper level, and propose their desired reliability demand and reliability principal–agent incentives to IEO individually, to maximize their energy utilization within the limited reliability resources.

The operation reservations dispatch is based on the energy transaction prices in the external day-ahead market and the historical real-time market. In cooperative gaming, the IEO makes optimal decisions based on the users' actual reliability benefits and reliability improvement costs of each user at the lower level, and the improvement degree of reliability depends on the declared energy utilization of the users and the commissioning principal–agent contract. The user pays for the reliability improvement cost to the IEO.

5. Solution of Bi-Level Optimization

In the proposed bi-level cooperative gaming model, the setting energy prices and the practical energy reliability information given by the IEO in the upper level will guide the users' energy strategies in the lower level, while the reliability incentive stated by the IEU in the lower level will affect the reliability costs and energy dispatching in the upper level in turn. This game process demonstrates how the users affect the reliability allocation in IEM. It also shows how the energy dispatching balances the need for energy reliability with its economics.

Since the lower-level problem is continuous and convex, the objective function and constraints of the lower-level model can be replaced by its KKT conditions as the constraints of the upper level. After that, the bi-level optimization problem becomes a mixed-integer linear programming (MILP), which simplifies the solving difficulty of the problem.

Since the transformed single-level problem is nonconvex, there exists a non-linear term $\beta^{x}_{i,t}(\widehat{LOLP}^{x}_{i,t} - LOLP^{x}_{i,t})$ in complementary condition and the objective function. It requires a transformation of the relaxation condition to reduce the solving difficulty of the problem. As the low-level model is convex and linear, which indicates that it obeys the strong duality theorem; accordingly, the initial objective can be described as a typical mixed-integer linear programming (MILP) by the strong duality theorem and the Big-M method.

In this case, the bi-level problem can be solved successfully with the YALMIP toolbox on the platform of MATLAB by invoking the GUROBI solver. The practical hardware environment of the test system is Intel i7-8700 CPU 3.20 GHz, 8 GB RAM, the operating system is Win10 64 bit; and the development environment is MATLAB R2019a.

6. Case Study

An Asian pilot IEM is taken as a case to simulate the proposed energy dispatching model considering the reliability principal–agent contact. Since the model involves the heating part, and it is only winter that has heating supply, this paper only simulates the bi-level optimization game in winter conditions.

The voltage of the distribution electricity network in IEM is 10 kV, and three IEUs are considered to take part in the reliability principal–agent, which contains commercial, official, and industrial users, and it is suitable for analysis and comparison due to their diversity and representativeness of reliability demand characteristics in time and space dimensions.

The IEM contains one wind turbine, one photovoltaic unit, two CHP units, and one gas boiler. The load types in the users are electric load and heating load. The IEO gives priority to dispatching units within IEM, and when sudden problems occur on the units, priority is given to dispatch other units within the region; if the supply shortage amount is too large, IEO will consider purchasing energy reservations from the external energy market to ensure system operation and meet users' reliability demand. The overall energy structure of this IEM is shown in Figure 3. Since the energy generating units in IEM are usually close to the load centers and the topology of the distribution network and heat network is relatively simple with few nodes, we assume that there is no energy flow blockage.

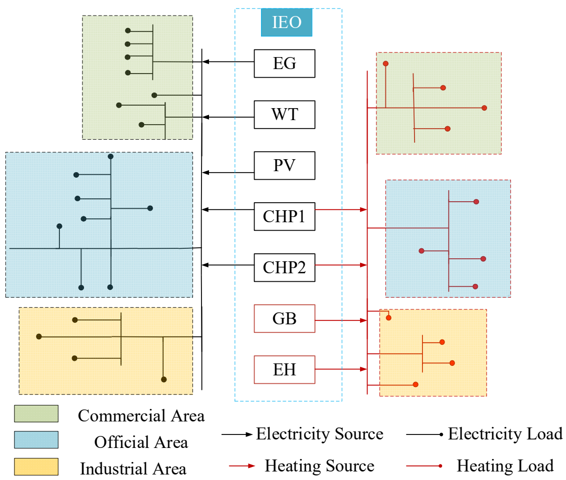

Figure 3. The energy frameworks of the pilot IEM.

To verify the effectiveness of the proposed reliability principal–agent contract on energy dispatching, the following two modes are set to simulate and compare reliability and economic effect.

Original Mode: Keep the original dispatching mode without considering the reliability principal–agent contract;

Incentive Mode: Dispatching energy in the bi-level program considering the reliability principal–agent contract.

6.1. Comparison of Cost and Benefits of Reliability Improving

To verify the optimal dispatching model's economic benefits on the dispatch cost of IEO and the energy benefit of IEU considering the reliability principal–agent contract, this part compares the original mode and the incentive mode, to obtain the increased energy benefit of the users due to the reliability improvement and the benefit of IEO due to the reduced operational dispatch cost. At the same time, the reliability improvement costs for the electricity part and the heating part are compared to see the benefits improvement degree of each energy system in the context of this case.

As shown in Table 1, in the optimal dispatch considering the reliability principal-agent contract, with allocating reliability improving incentives from users to acquiring and optimizing energy reservation, IEO provides energy auxiliary services for users. From the table, it can be obtained that the cost of heating reliability improving is slightly lower than the electrical part. Among them, electric energy accounts for 56% of the total cost of reliability improving, and heating energy accounts for 44%. However, for the benefits from the reliability improvement of the users, electrical energy accounts for 40% and heating energy accounts for 60%, which shows the cost-effectiveness of heating reliability improvement is more significant than that of electricity. Consequently, in fund-limited situations, they are more likely to give priority to heating reliability improvement. At the same time, the overall net profit of both the users and the IEO is improved. For IEO, the overall dispatch cost was optimized by 27.3% due to the change in energy structure guided by the reliability principal–agent contract. This shows that the optimal dispatching model considering the reliability principal–agent contract has economic superiority and can lead to a win–win situation for all parties.

Table 1. Costs and Benefits of Reliability Improving.

	Reliability Improving Cost (USD)	Users' Improving Gain (USD)	IEO Improving Profit (USD)
Electricity	224,221	340,208	525,182
Heating	175,871	509,806	
Total	400,092	850,014	

6.2. Comparing Reliability of Multiple Types of Users during Peak and Valley Times

To verify that the optimal dispatching model considering the reliability principal–agent contract can meet the diversity of reliability improving demands of multiple users at different periods, this section demonstrates the reliability index of three types of users during the peak and valley times of system energy use. Considering that the reliability demands are differentiated due to their profitability, initial reliability, and system reliability resource tension, two representative periods with different characteristics at 10:00 and 20:00 are selected for comparison in this section to verify the effectiveness of the model in personalized quality improvement service.

Comparing the energy reliability changes of different users between the peak and trough period, as shown in Figures 4 and 5, all types of users' energy reliability improves to different degrees, but there is variability in the improvement degree due to the users' different reliability needs at different times. Comparing Figures 4 and 5, for commercial users, 10 o'clock and 20 o'clock are both their earning time, so their electricity and heating reliability is greatly improved at that time. However, because 20 o'clock is more important, there is a slight increase in the reliability during this time compared to the former. For official users, energy is more profitable at 10 o'clock than at 20 o'clock; therefore, their reliability both improved to a greater degree at 10 o'clock, while the degree of reliability improvement for 20 o'clock is less. The industrial users' loss of energy supply interruption is lower than the formers, so they have the lowest desire to seize reliability resources; at 20 o'clock, the reliability improvement is zero because of its being unprofitable. In addition, the overall degree of heating reliability improvement is higher than that of electricity, because the unit cost of heating reliability improvement is lower, and its cost-effectiveness for user profit improvement is stronger; therefore, there are more scenarios to give priority to heating reliability improvement in the limited fund allocation. In summary, after considering the reliability principal–agent, by energy dispatching optimization, the reliability resource allocation can be optimized according to the users' personalized demand, and the users' loss of energy supply interruption can be reduced; consequently, a win–win situation can be achieved under the cooperative game between IEO and users.

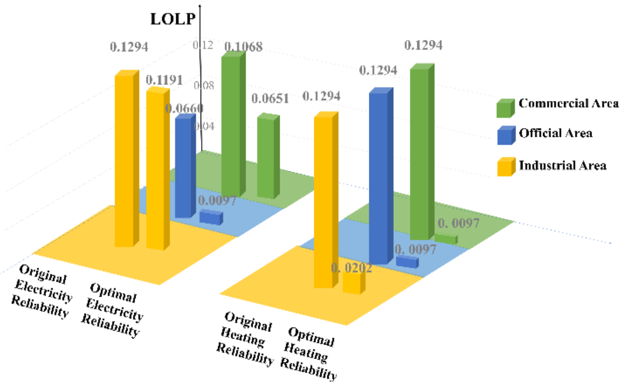

Figure 4. The energy reliability improvement for each user at 10:00.

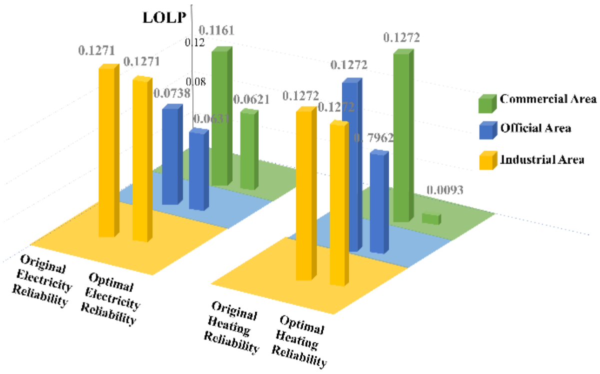

Figure 5. The energy reliability improvement for each user at 20:00.

6.3. Comparison of Energy Dispatching Structure under Normal Operation Scenario

To explore the impact of the proposed model on the basic energy dispatch situation under normal operation scenarios, this section compares the energy dispatch of IEO for each unit's output in original mode and incentive mode, comparing the proportion of each unit's output in the electricity part and heating part under different modes. As a result, it verifies the effectiveness of the model for optimizing the dispatch cost, and it verifies whether it is a good guide for the energy dispatching structure.

Compare the unit output situation in 24 h dispatching under different modes in a normal operation scenario. As shown in Figures 6 and 7, after considering the reliability principal–agent contract for energy dispatching, the CHP dispatch amount decreases, the WT and PV increase by 41.7% and 61.4%, respectively, and the GB also increases. This is because, in the original model, IEO dispatching amount is not much on WT and PV to ensure the reliable and stable operation of the system, and relies on CHP and GB which are highly reliable but more expensive units. However, after taking the proposed principal-agent contract, IEO can use the reliability incentive provided by the uses to purchase additional energy operation reservations, which makes the reliability of the system extra guaranteed and improved, and reduces the difficulty of operation and maintenance, providing more space for low-priced, sustainable energy to grow. At the same time, as CHP units adopt the "power to heat" model, the reduction of CHP using amount will increase the amount of GB in the heating system. From the viewpoint of energy structure, the optimal dispatching considering the reliability principal–agent mechanism can effectively improve the sustainable energy consumption capacity in the micro-grid, and the energy structure is developing in the direction of low carbon and environmental friendliness.

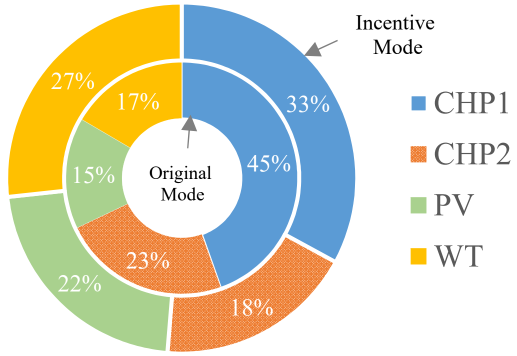

Figure 6. The units output situation in the electricity part.

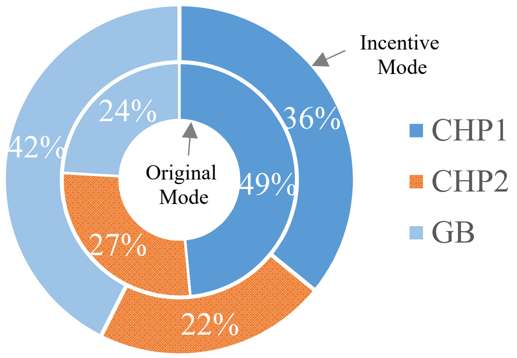

Figure 7. The units output situation in the heating part.

In addition, since the energy dispatch in the system normal scenario gives priority to using units within the micro-grid, but in the unit failure scenarios, the operation reservations dispatch will purchase reservations with the external grid and external heating network. Therefore, there is no external grid or external heat network output situation in this figure.

6.4. Reliability Transaction in the Incentive Mode

To demonstrate the transaction and interaction between IEO and IEUs in the proposed model, in terms of the campus structure, this section shows the reliability improving costs paid by users to IEO according to the reliability principal–agent contract, and the improved energy-use benefits for each user after the reliability has been improved by IEO are also shown. Thus, in the proposed model, the win–win results in terms of economics for both sides of the cooperative game are verified.

As Figure 8 shows, the users' energy utilization is improved to different degrees through the reliability principal–agent contract, and the benefits are much higher than the cost of reliability improvement. The largest transaction volume in the IEM is the official user, and the smallest is the industrial user. It is the reason that the official area has the largest energy-using volume in the park, and their losses are also heaviest when facing the load interruption, so their demand for reliability is large not only on the amount, but on quality. In contrast, the industrial user has small energy volume and has less reliability demand during the peak energy consumption period. In addition, the greater the cost paid for the reliability principal–agent contract, the more the reliability improvement benefits received for the user. For the more profitable users, like the commercial and official, the reliability principal–agent mechanism has a better effect on them and shows more significant economic returns. In summary, the integrated energy dispatching model considering reliability principal–agent contract requires certain reliability improving cost, but creates more benefits for each user in the IEM; in addition, users make personalized transactions according to their reliability demands, which can better achieve the optimization of reliability resource dispatching and thus maximize the welfare of the whole society.

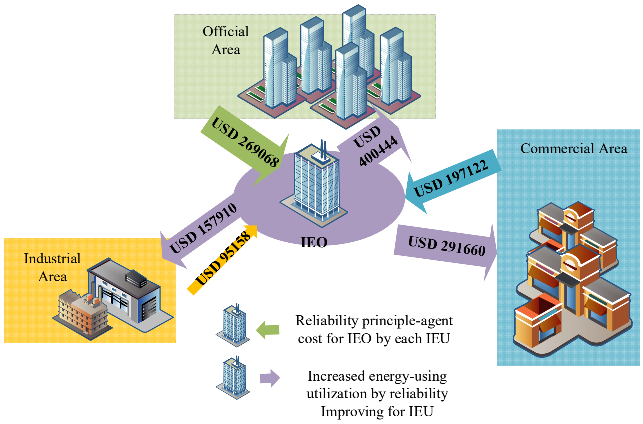

Figure 8. The reliability transaction in incentive mode.

6.5. Sensitivity Analysis on IEO Cost with user's Energy-Using Benefits

This part aims to explore the relationship between the four parts of IEO energy dispatch cost and the variation of the IEU's energy-use benefits b_i^x in the incentive mode. As shown in Figures 9 and 10, regarding the b_i^x in the above case calculation as the standard benefits, in the range of 0.6 times to 1.4 times, exploring the trend of the operation cost and reliability improving cost of the IEO in electric and heating energy.

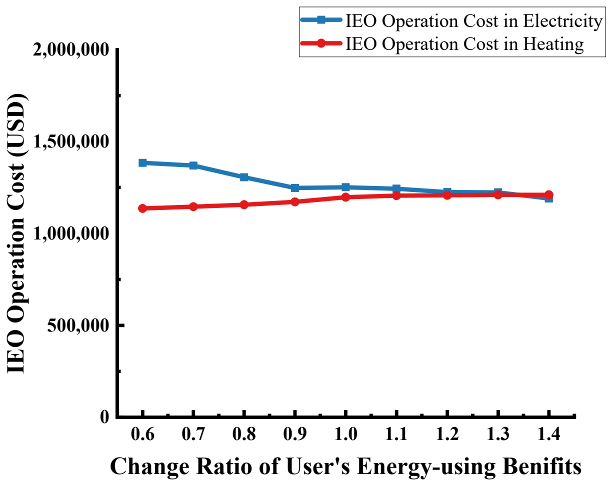

Figure 9. The sensitivity analysis on IEO operation cost with user's energy-use benefits.

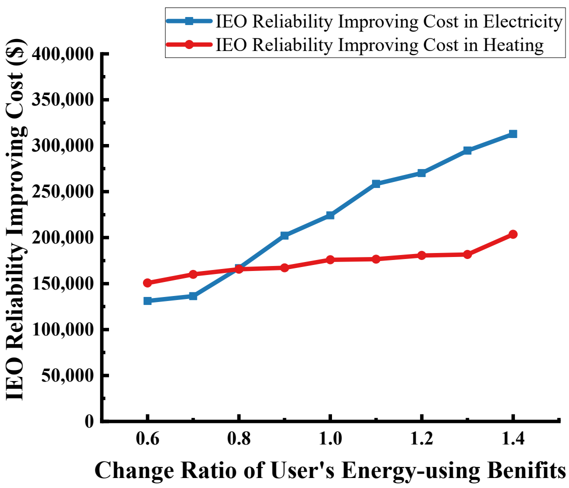

Figure 10. The sensitivity analysis on IEO reliability improving cost with user's energy-use benefits.

As can be seen from Figure 8, the operation cost of electricity energy tends to decrease as the user's energy-using benefits b_i^x increase, while the operation cost of heating tends to increase slowly. This is because the reliability principal–agent contract affects the structure of energy dispatching for IEO, as shown in Figure 6, the electric energy part tends to increase the dispatch amount of low-cost sustainable energy, which significantly reduces the operation cost of electricity. While the heating energy part has a slight increase due to the production pressure from CHP units shifting to GB units. For the electricity part, its operation cost first decreases significantly in the user's benefit smaller stage, and then the rate of decrease slows down. Due to the profit space that created by a large amount of low-priced renewable energy, which causes the operating cost to decrease significantly when the user's benefits are small. In addition, when the renewable energy penetration reaches a certain level, its growth space shrinks and the operation cost decreases slowly for the energy dispatch. For the heating energy part, the rising rate of its operation cost becomes slower gradually, because the cost difference generated by the adjustment of energy structure is not large, so the impact on its operation cost is small, but because the operation cost of GB is slightly higher than that of CHP, so its operation cost is slowly rising; as the growth of renewable energy penetration ratio becomes slower, its rising quantity is even slower on the energy dispatch changing amount.

As shown in Figure 10, the reliability improving cost tends to increase with the increase of user energy-use benefits b_i^x. This is because the increase in users' benefits will directly affect the size of the reliability principal–agent contract and the scope of reliability-improving funds available. In terms of electricity, the cost of improving reliability increases faster in the benefit smaller stage and slows down slightly in the later stage. This is because, within a certain range, it is easier to improve the reliability in the electricity part, and a larger improvement can be achieved at a lower cost; therefore, in this part, there is a large profit space for the reliability principal–agent on the IEU side, and the money amount for reliability improving rises significantly. However, as the degree of reliability increases, its unit reliability improving cost will become larger, and the profit margin from reliability improvement becomes smaller for users, so the growth rate of the volume of the reliability principal–agent contracts slows down, and thus, the growth rate of the money used by IEO for reliability improving also decreases slightly. For the heating part, its reliability improving cost is in a steady and slow growth state, which is because the heating reliability demand does not change much with the user's energy-use benefit, consequently, it is in a slowly rising trend.

7. Conclusions

In this paper, to realize the flexible and optimal allocation of energy reliability resources, and further explore the potential value of reliability resources from the perspective of the differentiation of users' reliability demands, we propose an optimal dispatching model in IEM considering the reliability principal–agent contract, verify its effectiveness and superiority through the case study, and obtain the following conclusions.

(1) In terms of economy, on the one hand, the model effectively reduces the energy dispatching cost of IEO, because of the improvement of reliability in the system, the space for low-price sustainable energy consumption is enhanced; on the other hand, the loss of energy supply interruption for IEUs is targeted, and their energy utilization are improved to different degrees, which realizes the win–win situation of multiple participants in the cooperative game.
(2) In terms of system reliability, the model optimizes the allocation of reliability resources by the market mechanism, which significantly improves the system reliability with low cost on IEO; each type of user within the IEM also achieves a personalized improvement of energy reliability in the time dimension.
(3) In terms of energy structure, the model can effectively improve the sustainable energy consumption capacity in the IEM, and promote the energy structure developing in the direction of low carbon and environmental friendliness.

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References

1. Krakowski, V.; Assoumou, E.; Mazauric, V.; Maïzi, N. Feasible path toward 40-100% renewable energy shares for power supply in France by 2050: A prospective analysis. *Appl. Energy* **2016**, *171*, 501–522. [CrossRef]
2. Jeong, J.; Shin, H.; Song, H. A Countermeasure for Preventing Flexibility Deficit under High-Level Penetration of Renewable Energies: A Robust Optimization Approach. *Sustainability* **2018**, *10*, 16. [CrossRef]
3. Tian, L.; Xie, Y.; Hu, B.; Liu, X.; Deng, T.; Luo, H.; Li, F. A Deep Peak Regulation Auxiliary Service Bidding Strategy for CHP Units Based on a Risk-Averse Model and District Heating Network Energy Storage. *Energies* **2019**, *12*, 27. [CrossRef]
4. Tsai, C.H.; Figueroa-Acevedo, A.; Boese, M.; Li, Y.; Mohan, N.; Okullo, J.; Heath, B.; Bakke, J. Challenges of planning for high renewable futures: Experience in the US midcontinent electricity market. *Renew. Sustain. Energy Rev.* **2020**, *131*, 14. [CrossRef]
5. Mohammadi, R.; Mashhadi, H.R.; Shahidehpour, M. Shahidehpour. Market-Based Customer Reliability Provision in Distribution Systems Based on Game Theory: A Bi-Level Optimization Approach. *IEEE Trans. Smart Grid* **2019**, *10*, 3840–3848. [CrossRef]
6. Yang, X.; Gu, C.H.; Yan, X.H. Reliability-Based Probabilistic Network Pricing with Demand Uncertainty. *IEEE Trans. Power Syst.* **2020**, *35*, 3342–3352. [CrossRef]
7. Yang, H.; Wang, L.; Zhang, Y.; Tai, H.M.; Ma, Y.; Zhou, M. Reliability evaluation of power system considering time of use electricity pricing. *IEEE Trans. Power Syst.* **2019**, *34*, 1991–2002. [CrossRef]
8. Wang, S.; Zhao, C.; Liu, L.; Xie, S. Reliability pricing method based on consumer-centric reliability metrics with the integration of energy storage system. *Energy Procedia* **2019**, *158*, 4160–4165. [CrossRef]
9. Zhai, J.; Wu, X.; Zhu, S.; Yang, B.; Liu, H. Optimization of Integrated Energy System Considering Photovoltaic Uncertainty and Multi-Energy Network. *IEEE Access* **2020**, *8*, 141558–141568. [CrossRef]
10. Fumagalli, E.; Black, J.W.; Ilic, M.; Vogelsang, I. A reliability insurance scheme for the electricity distribution grid. In Proceedings of the IEEE Power Engineering Society Summer Meeting, Vancouver, BC, Canada, 15–19 July 2001. [CrossRef]
11. Abedi, S.M.; Haghifam, M.R. Comparing reliability insurance scheme to performance-based regulation in terms of consumers' preferences. *IET Gener. Transm. Distrib.* **2013**, *7*, 655–663. [CrossRef]
12. Fumagalli, E.; Black, J.W.; Vogelsang, I.; Ilic, M. Quality of service provision in electric power distribution system through reliability insurance. *IEEE Trans. Power Syst.* **2004**, *19*, 1286–1293. [CrossRef]
13. Liang, H.; Liu, Y.; Shen, Y.; Li, F.; Man, Y. A Hybrid Bat Algorithm for Economic Dispatch with Random Wind Power. *IEEE Trans. Power Syst.* **2018**, *33*, 5052–5061. [CrossRef]
14. Dong, J.; Zhu, L.; Dong, Q.; Kritprajun, P.; Liu, Y.; Liu, Y.; Tolbert, L.M.; Hambrick, J.C.; Xue, Y.S.; Ollis, T.B.; et al. Integrating Transactive Energy into Reliability Evaluation for a Self-healing Distribution System with Microgrid. *IEEE Trans. Sustain. Energy* **2022**, *13*, 122–134. [CrossRef]
15. Habibi, M.; Vahidinasab, V.; Pirayesh, A.; Shafie-khah, M.; Catalão, J.P. An Enhanced Contingency-based Model for Joint Energy and Reserve Markets Operation by Considering Wind and Energy Storage Systems. *IEEE Trans. Ind. Inform.* **2021**, *17*, 3241–3252. [CrossRef]
16. Zhang, Z.; Wang, C.; Lv, H.; Liu, F.; Sheng, H.; Yang, M. Day-Ahead Optimal Dispatch for Integrated Energy System Considering Power-to-Gas and Dynamic Pipeline Networks. *IEEE Trans. Ind. Appl.* **2021**, *57*, 3317–3328. [CrossRef]
17. Faridpak, B.; Farrokhifar, M.; Alahyari, A.; Marzband, M. A Mixed Epistemic-Aleatory Stochastic Framework for the Optimal Operation of Hybrid Fuel Stations. *IEEE Trans. Veh. Technol.* **2021**, *70*, 9764–9774. [CrossRef]
18. Chen, Z.; Zhu, G.; Zhang, Y.; Ji, T.; Liu, Z.; Lin, X.; Cai, Z. Stochastic dynamic economic dispatch of wind-integrated electricity and natural gas systems considering security risk constraints. *CSEE J. Power Energy Syst.* **2019**, *5*, 324–334. [CrossRef]
19. Yao, L.; Wang, X.; Qian, T.; Qi, S.; Zhu, C. Robust day-ahead scheduling of electricity and natural gas systems via a risk-averse adjustable uncertainty set approach. *Sustainability* **2018**, *10*, 3848. [CrossRef]

20. Wu, H.; Shahidehpour, M.; Li, Z.; Tian, W. Chance-constrained day-ahead scheduling in stochastic power system operation. *IEEE Trans. Power Syst.* **2014**, *29*, 1583–1591. [CrossRef]
21. Li, H.R.; Zhang, C.H.; Sun, B. Optimal design for component capacity of integrated energy system based on the active dispatch mode of multiple energy storages. *Energy* **2021**, *227*, 14. [CrossRef]
22. Cao, M.; Shao, C.; Hu, B.; Xie, K.; Li, W.; Peng, L.; Zhang, W. Reliability Assessment of Integrated Energy Systems Considering Emergency Dispatch Based on Dynamic Optimal Energy Flow. *IEEE Trans. Sustain. Energy* **2021**, *13*, 290–301. [CrossRef]