Paving the Way to Smart Micro Energy Internet: Concepts, Design Principles, and Engineering Practices

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Abstract—Energy internet is one of the most promising future energy infrastructures which could enhance energy efficiency and improve operating flexibility from the energy point of view. In analog to the micro-grid, micro energy internet puts more emphasis on the distribution level and demand side. The concept and design principles of the smart micro energy internet are proposed to accommodate micro-grids, distributed poly-generation systems, energy storage facilities, and related energy distribution infrastructures. The dispatch and control system of the smart micro energy internet should be responsible for external disturbance and able to approach a satisfactory operating point which compromises multiple criteria, such as safety, economy, and environment protection. To realize the vision of the smart micro energy internet, engineering game theory based energy management system with self-approaching-optimum capability are investigated. Based on the proposed concepts and design principles, and energy management system, a prototype of the first domestic conceptual solar-based smart micro energy internet is initially established in Qinghai University.

Index Terms—Smart micro energy internet, self-approaching-optimum, energy management, engineering game theory, solar-based smart micro energy internet.

I. INTRODUCTION

With the emergence of the energy crisis and environment issues, high-efficiency and environmentally friendly energy utilization systems are demanded urgently. It has been validated that the integration of different energy distribution systems could bring additional flexibility and reliability to system operation and enhance energy efficiency [1]. Thus, the coupling of energy infrastructures including district heating network [2][3], natural gas network [4][5], and electric vehicle transportation infrastructure [6][7] and power network has been investigated extensively to improve system efficiency and reliability.

Integrated energy system [1], energy internet [8], multi-source multi-product system [9], multi-energy system [10], as well as energy micro-grid [11] provide the possibility for the coupling among multi-carrier energy including electricity, natural gas, and heat. The integration of such infrastructures has been viewed as a promising future approach to realize the safe, cost-effective, and environmentally friendly energy supply [12][13].

Energy hub is one of the key components in the multi-carrier energy system, and it is capable of the conversion, transmission, and storage among multiple energy carriers [14]. Thus, the energy hub builds natural linkages among the traditional independent infrastructures including power distribution network (PDN), gas distribution network (GDN), district heating network (DHN), cold distribution network (CDN), and electrified transportation network (ETN) in the multi-carrier energy system. Combined heat and power unit with thermal energy storage[3], compressed air energy storage system [15][16], and concentrating solar power facility [17] are typical energy hubs with power and heat co-generation and storage capability. These hubs have been applied in both transmission-level and distribution-level coupled energy systems [16]-[18].

Since energy distribution level simplifies the implementation of the coupled energy system functions, the research on the future form of such coupled infrastructures in the distribution level and demand side is of great interest [19]. Micro energy internet is one of such coupled system, which puts emphasizes on the integration of different energy networks at the distribution level. Specifically, micro energy internet is the distributed form of energy internet and it is composed of distributed renewable energy sources, energy storage facilities, multi-carrier energy sources, multi-carrier loads, and distribution infrastructures such as PDN, DHN, GDN, and ETN. Moreover, smart micro energy internet is formed by capturing the multi-criteria self-approaching-optimum ability as investigated in [20]. Based on the previous works in [16]-[20], the fundamental concepts and designing principles of smart micro energy internet is further exploited in this paper.

Although extra reliability and flexibility can be achieved by integrating the multi-carrier energy devices and different energy distribution infrastructures under the framework of the smart micro energy internet, energy management of such systems are challengeable due to the inevitable multiple decision makers with competitive or/and cooperative targets under the stochastic operation conditions and asymmetric market information [21]. Thus, traditional single-agent based control and decision theory cannot be responsible for these situations, an advanced modeling, analysis, and decision tool is essential for the energy management of the smart micro energy internet with multi-decision markers.

Game theory has been a fundamental mathematical tool of economists, politicians, and sociologists for decades due to its capability of solving decision-making problems involving multiple agents with cooperative or/and competitive goals [22].
The concepts, theories, and methodologies of game theory can be used to guide the resolution of engineering design, operation, and control problems in a more canonical and systematic way [23] [24]. It has been widely used in smart grid planning, economic dispatch, market equilibrium analysis [24]-[27]. Undoubtedly, engineering game theory is a powerful tool to develop advanced dispatch and control scheme for the smart micro energy internet. Thus, engineering game-theoretic methods based dispatch and control system is investigated to realize the self-approaching-optimum energy management of the smart micro energy internet in this paper.

Compared to developing advanced energy infrastructures, construction of the engineering demonstration site is also of great importance. To this end, the prototype system of a solar-based smart micro energy internet has been established under the guidance of the smart micro energy internet framework in Qinghai University, China. The whole system is composed of three kinds of solar-based power and heat sources, including multi-function PV station, solar chimney power station, and full solar spectrum power generation, an energy hub based on solar-thermal compressed air energy storage system (ST-CAES), a smart micro-grid for library with building integrated photovoltaics, power and heat loads such as carbon fiber recycling system and campus load, and the engineering game theory based self-approaching-optimum energy management system.

The rest of this paper is organized as follows. Section II proposes the vision of the smart micro energy internet in a comparative way, and give rise to the concepts and design principles of the smart micro energy internet. Multi-criteria self-approaching-optimum energy management scheme based on engineering game-theoretic methods for the smart micro energy internet is developed in Section III. The conceptual solar-based smart micro energy internet prototype system is presented in Section IV. Conclusions are drawn in Section V, and the intriguing research directions are also envisioned.

II. TRANSITION TO THE SMART MICRO ENERGY INTERNET

Many solutions including smart grid, integrated energy system, and energy internet have been proposed to satisfy the increasing energy demands in a secure and reliable way. However, most of these concepts mainly focus on the transmission level while much less attention was paid to the distribution level and demand side. Considering the high-efficiency and flexibility characteristics of distributed co-generations, we focus more on the distribution level and demand side to accommodate micro-grids, distributed poly-generation systems, energy storage facilities, and related energy distribution infrastructures in the framework of the smart micro energy internet. This section is dedicated to exploiting the concepts, design principles, and vision of the smart micro energy internet.

A. From Smart Grid to Smart Micro-grid

As a typical next generation electric power system, smart grid has been studied for decades. The smart grid is a modern electric power grid infrastructure for improved efficiency, reliability and safety, with smooth integration of renewable and alternative energy sources, through automated control and modern communications technologies [28][29]. To simplify the implementation of smart grid functions, such as reliability, self-healing, and load control, the concept of micro-grid has been proposed [19].

Micro-grid has been regarded as the distributed way of the smart grid, and it has two fundamental operation modes, the autonomous mode and the grid-connection mode [30]. Since the micro-grid pays more attention to the distribution level and demand side, the generated power in micro-grid is mainly for self-use in the autonomous mode. Insufficient or surplus power can be regulated with the connected PDN or power utility in the grid-connection operation mode.

Micro-grid with self-approaching-optimum energy management and satisfied multi-criteria on safety, economy, and environment protection can be treated as a smart micro-grid. Thus, self-optimum-approaching dispatch and control center is necessary for the energy management system of the smart micro-grid. Advanced energy management strategies for both smart grid and micro-grid have been investigated to exploit the functionality of such advanced smart energy infrastructures in [31]-[33]. With the popularity of distributed CHP and micro-CCHP, the smart micro-grid is capable of supplying cooling, heating, and power for the demands from residents, industrial, and commercial areas to yield a CCHP micro-grid [34]. Similar to traditional micro-grid, CCHP micro-grid also requires flexible operation in both autonomous mode and energy distribution infrastructures connected mode. Thus, a smart distribution-level energy infrastructure is required to facilitate the plug and play of such CCHP micro-grids. Smart micro energy internet is a perfect framework to implement this function.

B. From Energy Internet to Smart Micro Energy Internet

Energy internet is an energy management system with the power system as its core, smart grid as the basis, to incorporate renewables and accommodate multi-carrier energy for improving the overall energy utilization ratio with the advanced information, communication technologies and power electronic technology [35][36]. Inside an energy internet, an energy hub is a key facility in which multiple energy carriers can be converted, conditioned, and stored. To be more specific, energy hub represents an interface between different energy infrastructures and/or load in energy internet. Energy hubs consume power at their input ports, e.g., electricity and natural gas infrastructures, and provide certain required energy services such as electricity, heating, and cooling at the output ports. Although energy hub connects multiple infrastructures in an energy internet, the complexity of energy internet put barriers to the realization of the predefined functions of the energy internet.
To facilitate the functions of the energy internet on the distribution level, we investigate the smart micro energy internet as a class of energy network composed of PDN, DHN, and district cold network with energy hubs. The architecture of a networked smart micro energy internet is depicted in Fig. 1. Energy infrastructures including electricity, district heating, natural gas, and transportation network are coupled through energy hubs such as CAES, electric vehicle, heat storage system, and refrigerator. We can conclude form Fig. 1 that, the networked smart micro energy internet are connected with energy utilities, including natural gas grid, power grid, and thermal grid. Inside a smart micro energy internet, several energy distribution infrastructures are integrated with each other through energy hubs, or distributed poly-generation systems, or energy storage systems. Specifically, in the smart micro energy internet B, the interconnections among different distribution infrastructures can be clarified as follows:

- PDN and ETN are integrated with the electric vehicle charging station.
- Compressed air energy storage system builds the linkage among PDN, DHN, and CDN.
- Gas boiler connects the DHN and GDN.

To design a smart micro energy internet, several fundamental principles are necessary, and indicated as follows:

- At least one clean energy resource is integrated;
- Energy storage facility with sufficient capacity is deployed;
- Electricity acts as the main energy carrier and distributed with the heat and cool energy;
- The energy is mainly for self-use especially on demand side;

- A multi-criteria self-approaching-optimum energy management system in incorporated to capture the unattended capability.

It should be mentioned that the “multi-criteria self-approaching-optimum” is a framework, it is composed of two fundamental aspects. The first is the “multi-criteria”, which requires the designed system to be operated in the sense of multi-criteria from the perspective of operation targets. The definition of “multi-criteria” can be be case by case, as for the micro energy internet, it includes the economic, security, and environmental aspects. The second aspect is the “self-approaching-optimum”, which describes the ability of find the optimum operation point by itself, i.e. intelligent or smart. Definitely, the realization of “multi-criteria self-approaching-optimum” depends on mature optimization approaches, including both traditional methods as well as advanced methods. In this respect, the multi-criteria self-approaching-optimum is a good choice for the operation of the smart micro energy internet.

As indicated in Section II. A micro-grid is usually connected to PDN which is integrated into the smart micro energy internet. Therefore, the concept of the micro-grid within the scope of the smart micro energy internet. Under the vision of energy internet, the grid-connection mode of micro-grid refers to its connection to the smart micro energy internet.

The smart micro energy internet can accommodate the traditional smart micro grid. Thus, the voltage level, capacity/demand of electricity is similar to that of smart micro grid. As for the heating network, since most of existing district heating network is distributed locally, it is natural to be integrated to the proposed smart micro energy internet, especially for the 4th generation of district heating and cooling.
techniques[13]. The key parameters in district heating system are the temperature at the supply and return systems, as well as the hydraulic distribution along the piping networks. The interconnection points between the electric part and heat part of smart micro energy internet are the co-generation units as well as the energy hubs. The integration of the smart micro energy internet with the utility infrastructure is realized by its connection to energy utilities, including power grid, gas grid, and thermal grid. For the case of gas network is available, a local gas distribution network can also be incorporated in the smart micro energy internet as shown in Fig.1. In this case, the interconnections among distribution level infrastructures are realized gas-fired CHP, gas-fired CCHP, as well as the energy hubs.

We firmly believe that the implementation of the smart micro energy internet can simplify the realization of many energy internet functions, including multi-carrier energy synergy, incorporating more renewable energy resources, and improved reliability. Definitely, the performance of the smart micro energy internet depends on its dispatch and control strategies. A multi-criteria self-approaching-optimum operation energy management system is required to realize the secure, cost-effective, and environmentally friendly operation of the smart micro energy internet [20].

III. ENGINEERING GAME-THEORETIC METHODS FOR THE SMART MICRO ENERGY INTERNET

Smart micro energy internet is typically characterized by incorporating multiple energy sources (wind, PV, natural gas suppliers, heat suppliers, etc.), multi-network (power network, gas network, heating network, cooling network), multi-user (power users, heat users, natural gas users, central air conditioning systems, etc.) and multiple energy forms (electricity, gas, heat, cool, etc.). Thus, the smart micro energy internet is typically a complex stochastic system integrated laterally by electricity, gas, heat, cold, and other energy distribution infrastructures, and composed longitudinally by different decision-making agents including energy suppliers, dispatch centers, and multiple users. In this regard, the planning and energy management of the smart micro energy internet calls for advanced methods.

As indicated previously, game theory puts more emphasis on the decision behaviors of each player with compete or cooperate goals, based on the collected information. Engineering game theory pays more attention to the applications of fundamental concepts, modeling, and solution methods of game theory to the decision problem of engineering design and experiment by taking the engineering practical conditions into account [24]. Motivated by [40], we develop engineering game-theoretic methods for the smart micro energy internet in this section.

A. General Remarks

The engineering game theoretic methods are originated from our work in the vision of smart grid. By following the fundamental motivation to convert the decision and control problems in engineering to mathematical problems with the game modeling techniques, and solved by equilibrium solution methodologies, to provide the engineering decision-maker a competitive and optimized solution. Different from traditional game-theoretic methods put more emphasis on the competitive status among decision players, engineering game-theoretic methods pay more attention to the competitive behavior among human and the nature, thus builds the bridge from traditional game-theoretic methods to engineering applications, such as planning and energy management of the smart micro energy internet. The fundamental motivations of the engineering game-theoretic methods can be illustrated as:

\[
\min_{x_1, x_2} f_1(x_1, x_2) \min_{x_1, x_2} f_2(x_1, x_2) \tag{1}
\]

where nature \(x_1\) is a fictitious player, with rationality \(f_1(x_1, x_2)\), and strategy set \(X_1\) while \(x_2\) denote the decision maker, with the utility function \(f_2(x_1, x_2)\), and strategy set \(X_2\). The analysis of nature’s rationality and modeling of strategy set is difficult. The basic connotation of engineering game-theoretic methods is depicted in Table I.

| Table I General Remarks for Engineering Game-Theoretic Methods |
|------------------|------------------|------------------|
| Decision problem | Game model       | Solution method  |
| Multi-objective  | Stationary game  | Nash equilibrium |
| Robust control   | Differential game| Feedback Nash equilibrium |
| Robust optimization | Zero-sum game    | Saddle Nash equilibrium |
| Multi-level optimization | Leader-follower game | Nash-Stackelberg-Nash equilibrium |
| Security defense | Security game     | Bayes-Nash-equilibrium |
| System evolution | Evolution game    | Evolutionary stability equilibrium |

B. Planning of the Smart Micro Energy Internet

The planning of the smart micro-energy internet mainly focuses on the optimal allocation and size of energy hubs, distributed generators, etc. Since power distribution, natural gas transportation, district heating infrastructures are usually existed, the planning issue of smart micro energy internet here mainly intends to the energy hubs. Specifically, the energy hubs in a smart micro energy internet are required to capture the features of combined heat, power, and cool generation and storage. Thus, an energy hub is usually an integration of different components, including transformer, micro-turbine, heat exchanger, furnace, absorption chiller, power energy storage unit, and hot water storage.

Taking the feasibility into account, an optimal selection of these components is essential for the smart micro energy internet as in [43]. Cost saving and emission reduction are the fundamental criteria for the smart micro energy internet. In this perspective, the optimal allocation and size of energy hub is multi-criteria one, multi-objective programming methods are usually adopted to handle this kind of problem. In general, it is difficult to reach the two minimums simultaneously due to the contradiction between carbon emission and system cost. Therefore, lots of evolutionary algorithms (EA) with the capability of providing many non-inferior solutions have developed to tackle this problem. EA methods have been viewed as effective ways to obtain the Pareto front. However, in actual smart micro-energy internet, the decision-maker needs one balanced solution, it is difficult to select one from the
Pareto front.

Stationary game based multi-objective optimization methods can be adopted to determine a balanced solution from the Pareto front. Three methods including comprehensive method, weighting method, Nash bargaining method have been proposed in [24]. The readers can refer them to get a more detailed elaboration. In this subsection, we focus on the Nash bargaining method of the most commonly bi-objective optimization. Specifically, planning problem in terms of cost saving and emission reduction can be generalized as:

$$\min \{ f_1(x), f_2(x) \}$$

s.t.  \( g(x) = 0, h(x) \leq 0, x \in \mathbb{R}^n \) \hspace{1cm} (2)

Where \( f_1(x), f_2(x) \) respectively denote the cost and carbon emission while \( g(x) \) and \( h(x) \) are the constraints.

In the perspective of engineering game theory, the two objectives in (2) are treated as two virtual players who negotiate with each other on how to distribute the planning resources. Based on the Nash’s theory, the bargaining solution of (2) is the optimal solution of (3)

$$\max_{x \in X} \left( f_1^d - f_1(x) \right) \left( f_2^d - f_2(x) \right)$$

(3)

Where \( f_1^d, f_2^d \) are the maximum cost and carbon emission. The problem (3) can be solved by a univariate parametric method such as golden section search algorithm. The Nash bargaining method herein can be directly extended to multi-objective one. Another advantage of the Nash bargaining method lies in no weight parameter is needed to normalize the magnitudes of the two objectives, i.e., it remains invariant under linear transformation of the objective function.

C. Hierarchical Energy Management of the Smart Micro Energy Internet

The coupling among multiple physical systems, multiple decision-making agents, and stochastic market environment make the dispatch and control of the smart micro energy internet challengeable. In this regard, to achieve multi-criteria self-approaching optimum dispatch and control for the smart micro energy internet, we propose an engineering game-theoretic based hierarchical energy management scheme in this subsection. The whole energy management system consists of three layers: utility connection layer, intra energy net layer, and the component layer as illustrated in Fig. 2.

1) Utility Connection Layer

This layer decides the operation mode of smart micro energy internet according to the prices of electricity and fuels in the energy market and other information such as power demands and weather predictions. For the grid-connection mode, the exchanged multi-carrier flow among networked smart micro energy internets and the connected energy utilities, also the exchanged multi-carrier energy with other smart micro energy internets should be determined. For autonomous mode case, the exchanged multi-carrier flows among micro energy internets and energy utilities are set to zero. Considering the fact that there are multiple decision makers in this layer, it is challengeable to determine the exchanged multi-carrier flow among micro energy internets due to the inevitable competitive or/and cooperative targets from the decision makers under the stochastic operation conditions and asymmetric market information[38][39].

To this end, engineering game-theoretic based methods can be adopted to handle this challenge while considering the utility of different market participants in terms of safety, economy, and environment protection criterions [40]. The decision behavior among the smart micro energy internets can be formulated as a Nash game in terms of cooperative or non-cooperative targets. Then, the exchanged power can be determined by Nash equilibrium as suggested in Fig.3. Once the exchanged power flow is regulated, the integrated optimal power flow (IOPF) among multi-carrier energy within the smart micro energy internet can be determined by the Intra-Energy-Net layer.

2) Intra-Energy-Net Layer

Optimal power flow among multi-carriers is needed for the integrated energy infrastructures [41]. The Intra-Energy-Net layer is responsible for the determination of IOPF within the smart micro energy internet once the exchanged power is calculated in the utility connection layer. According to the features of multi-carrier and energy infrastructures, the IOPF of the smart micro energy internet usually contains multi-decision makers and has multi-time scale characteristics. The determination of IOPF is also challengeable since the multi-decision makers may have a competitive or cooperative utility function.

When it comes to a specific smart micro energy internet that incorporating natural gas, district heating, and power distribution network with CHP, three types of dynamics exist in different time-scale: thermal dynamic, gas and electrical dynamic. To overcome the multi-time-scale characteristics, the Intra-Energy-Net layer can be further divided into three sub-layers to handle the slow, medium, and fast control layer as in [42]. To address the feature of multiple decision makers, which is important since infrastructures are usually owned by different utilities in today’s energy market, two situations are needed to be considered. In the first case, different infrastructures have the same decision maker. This can be solved with a cooperative game. In the second case, different infrastructures have disparate decision makers. This case can be handled by the non-cooperative game as depicted in Fig.3, thus yield a leader-follower game.

Once the IOPF within the smart micro energy internet is determined, the dispatch strategies and instructions can be performed by each component including distributed poly-generation unit, energy hubs and energy storage facilities through the component layer.
The component layer is responsible for the real-time control of the device in the smart micro energy internet to execute the setting points from Intra-Energy-Net layer. These devices usually suffer from external disturbance such as measurement noise, and internal disturbance such as unmodeled dynamics. Therefore, the control strategies for the devices in this layer need to be robust to follow the setting values.

The differential game based robust control is a proper candidate for this scenario, which treats uncertainty as a fictitious player competing with human-player to decide the performance of the devices. Mathematically, the controlled device in the smart micro energy internet can be modeled as:

$$\begin{align*}
\dot{x} &= f(x) + g_1(x)w + g_2(x)u \\
z &= h(x) + k(x)u
\end{align*}$$

(4)

Where $f_1(x), g_1(x), g_2(x), h(x), k(x)$ are the device dynamics, $x$ is the state variable, $u$ the control variable, and $w$ models the uncertainty. The human decision-maker has the goal of minimizing the utility function:

$$J(u,w) = \int_0^T \left( \|x\|^2 - \gamma^2 \|w\|^2 \right) dt \leq 0, \forall T \geq 0$$

(5)

While the uncertainty wants to maximize $J(u,w)$, thus yields the differential game model of robust control:

$$\min_{u} \max_{w} J(u,w) \leq 0$$

s.t. $\dot{x} = f(x) + g_1(x)w + g_2(x)u$

(6)

The control law can be obtained by solving the differential game to find the feedback Nash equilibrium. Several kinds of feedback Nash equilibrium seeking methods, including variable metric feedback linearization, controlled Hamilton designing method, policy iteration method, and approximated dynamic programming method are summarized in [24].

### IV. ENGINEERING IMPLEMENTATION: SOLAR BASED SMART MICRO ENERGY INTERNET

Besides developing energy management scheme, the construction of the smart micro energy internet is also critical. To this end, the first domestic implementation of the conceptual solar-based smart micro energy internet is realized in Qinghai University. The motivation is to develop a totally clean smart micro energy internet with advanced solar energy utilization techniques. The fundamental idea is to generate electricity and thermal energy with PV and solar thermal techniques. The produced electricity can then be either injected to the smart micro energy internet for self-use or be stored in the energy storage system. Meanwhile, the electricity power can also be fed into the PDN. Heat collected by parabolic trough collectors can either be used to generate electricity through a turbine or directly fed into the DHN. Usually, the power and heat demands can be fulfilled by the smart micro energy internet itself. For specific cases, the demands can be supplied by the power utility the solar-based smart micro energy internet connected to.

The constructed solar-based smart micro energy internet is composed of three kinds of solar-based power and heat sources: multi-function PV station, solar chimney power station, and full solar spectrum power generation. Besides, it also contains an energy hub based on solar-thermal compressed air energy storage facility, a smart micro-grid for the library with building integrated photovoltaics (BIPV), power and heat loads such as carbon fiber recycling system and campus load, and the engineering game-theoretic methods based multi-criteria self-approaching-optimum energy management system. The construction of this smart micro energy internet is finished in August 2016. The layout and the multi-carrier energy flow of the smart micro energy internet are shown in Fig. 4. Subsystems and energy management center of the solar-based smart micro energy internet are elaborated as follows.
A. Energy Hub: ST-CAES

The solar-thermal compressed air energy storage system is a typical CAES facility which captures the features of zero-carbon emission, collecting and recycling of air compression heat and solar thermal, and combined heat and power energy storage and tri-generation. It creates the link among the power network, cold network, as well as heat network in the constructed solar-based smart micro energy internet. The ST-CAES acts as an energy hub and its architecture is shown in Fig. 5.

The operation of the ST-CAES system includes two fundamental processes. During the charging process, low-quality electricity, including curtailed wind, solar, hydro power, and off-peak electricity are utilized to drive the compressor to generate high-pressure air stored in pipeline steel. Meanwhile, solar thermal collected by parabolic trough collectors (PTCs) during fine weather and the heat generated along with air compression are stored in the thermal storage tank. During the discharging process, the stored high-pressure air is preheated with the stored thermal energy to drive the high-speed turbine generator to produce electricity. The utilization of collected solar thermal energy improves the temperature of suction air of high-speed turbine generator and also increases the efficiency of the ST-CAES. The surplus thermal energy can be used heat generation. Moreover, the exhaust air of turbine can be used to cooling by regulating the temperature of the suction air. Thus, the ST-CAES allows the transfer of power, heat, and cooling in space and time and it is typically a combined cooling, heating and power energy storage system.

The energy hub model for the ST-CAES is illustrated in Fig. 6. Detailed dispatch model and the effectiveness of CAES hub in a typical smart micro energy internet contains PDN and DHN are investigated in [16].
B. Solar-thermal based Carbon Fiber Recycling System

In the constructed solar-based smart micro energy internet, a solar-thermal based carbon fiber recycling system is deployed as power load. The architecture of this system is depicted in Fig. 7. The system is composed of controllable solar reflectors, concentrators, pre-treatment platform, fine treatment furnace, and solar thermal storage tank, etc. The fine furnace adopts molten salt as the heat transfer material whose temperature can reach 600 °C with a ±2°C tolerance, thus the system can be regarded as a class of solar thermal power station technically.

In short, although the system is used for recycling carbon fiber material, its function is equivalent to a solar thermal power plant. In this regard, this subsystem can be viewed as either a power load or energy hub with combined heat and power generation capability, and its energy hub model is similar with the CSP in [17].

Fig. 7 Solar-thermal based carbon fiber recycling system

C. Power Sources in the Smart Micro Energy Internet

Since the essence of the solar-based smart micro energy internet is to utilize solar energy as the source for each energy carrier, power sources are all based on existed solar utilization techniques, including photoelectric conversion technology, thermoelectric conversion technology, and combined photoelectric and thermoelectric technique. The representatives of such techniques in the constructed smart micro energy internet are respectively the multi-function PV station, the plateau solar chimney power station, and the full solar spectrum power station as shown in Fig.8-Fig.10.

Fig. 8 Multi-function PV station.

1) Multi-function PV Station

Multi-function PV station is one of the main power sources for the smart micro energy internet. Its annual power generation capacity can reach 80,000 kWh. The generated electric power is mainly consumed by the campus. The PV station consists of 6 kinds of photovoltaic cell assembly, including monocrystalline, polycrystalline, double-sided, cadmium telluride, amorphous, and copper indium gallium selenide, 3 kinds of inverters, including micro-inverters, intelligent optimizer, and string inverter, and 10 combinations incorporating different modules, inverters, and bracket.

2) Plateau Solar Chimney Power Station

As a representative of thermoelectric technique, the solar chimney power generation system is mainly composed of heat-collecting shed, turbine, chimney, and heat storage layer. Solar thermal is utilized with the purposes of enhancing the air temperature of heat-collecting shed, reducing air density, and generating pressure difference with ambient environment. The air is then drawn by the chimney to generate updraft air flow to drive the turbine to produce electricity. This subsystem features no pollution during the operation, easily set up in desert and gobi, and local environment improvement with its greenhouse effect.

Fig. 9 Plateau solar chimney power generation.

3) Full Solar Spectrum Power Generation

Generally, 99% of the solar radiation energy locates in the wavelength range from 200 to 3,000 nm. 58% of this solar energy is distributed in ultraviolet and visible light with 200–800 nm wavelength, while 42% energy is in infrared light with the wavelength coverage of 800–3,000 nm. In this regard, photoelectric technique and thermoelectric technique individually utilize 58% and 42% of the solar radiation energy to produce electricity. However, since these two techniques rely heavily on the conversion material, the efficiency is usually low due to the fact that only partial spectral range of the solar radiation energy is utilized.

The essence of the full solar spectrum power generation system is to integrate solar thermoelectric conversion technique and photoelectric conversion technique to yield a high efficiency combined thermoelectric and photoelectric power generation technique. The fundamental principles of full solar spectrum power generation technique and schematic of the system is shown in Fig.10.

D. Solar-based Micro-grid with BIPV Technique

Building integrated photovoltaics has been regarded as one of the main development tendencies for the urban buildings and energy systems as it is the most efficient way to realize distributed PV generation and micro-grid techniques. BIPV combines PV and building, no extra floor space is needed, thus local accommodation is the best application form of PV in urban areas, especially, far-western region of China. In this
respect, a solar-based micro-grid with BIPV technique is built for the library as shown in Fig. 11.

The solar-based micro-grid is the first BIPV innovation platform in Qinghai province and it realizes the coordination between green energy technologies and modern architecture beauty. This micro-grid is actually a CCHP micro-grid and it is connected to the solar based smart micro energy internet. Thus, the library micro-grid can act as an energy source as well as energy load depending on its operation mode.

**E. Energy Management System**

Energy management of the multi-function PV station and BIPV based micro-grid are illustrated in Fig. 12. The accumulated generated electricity respectively reaches 109.91 MWh and 20.88 MWh. Since there is no other smart micro energy internet, the utility connection layer decides the operation mode of this micro energy internet, and it calculates the unbalanced energy demand. The intra-energy-net layer guarantees the optimal energy distribution among the three power sources, energy hub, library micro-grid, and carbon fiber recycling system. The component layer follows the dispatch instructions from intra-energy-net layer to control robustly the operation of PV station, full solar spectrum system, solar chimney power station, compressed air energy storage system, and micro-grid.

![Monitor system of the multi-function PV station](image)
Fig. 12 Monitor system of the multi-function PV station and the BIPV based micro grid

V. CONCLUSION

This paper proposes the concept, design principles of the smart micro energy internet to implement the vision of energy internet. Engineering game-theoretic methods based energy management scheme is proposed to realize the multi-criteria self-approaching-optimum operation of the smart micro energy internet. A solar-based conceptual smart micro energy internet prototype system has been established in Qinghai University. Micro energy internet is the distributed form of the energy internet, and the use of the micro energy internet can simplify the implementation of many energy internet functions. The smart micro energy internet is capable of multi-criteria self-approaching-optimum operation. Engineering game-theoretic methods provide effective ways to realize the real-time self-approaching-optimum dispatch and control strategies.

Definitely, the vision of the smart micro energy internet relies on substantial advances in intelligent distributed or decentralized control and decision mechanisms. Our further work will mainly focus on the development of engineering game-theoretic methods based distributed or decentralized control and optimization schemes and their implementations to the operation of the smart micro energy internet.

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