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Building a Zero-carbon Energy System towards Carbon-neutral Cities and its Pilot Application in China

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ABSTRACT

In the strategy of carbon peaking and carbon neutrality, cities and towns are the main battlefield while energy is the main force. Based on the synergy of multi-factors (source-network-load-storage) and multi-objectives (Lowest economic cost, lowest environmental cost, highest energy efficiency, highest electrification rate), built a zero-carbon energy system development planning model towards Carbon-neutral Cities.This paper presents the modeling approach of the zero-carbon energy system and presents its pilot application in Dazhangzhuang, one of the Smart Energy Town. To provide the reference for the construction of carbon-neutral cities energy system in China.

Keywords: carbon neutral, cities,energy systems,multi-objective

NONMENCLATURE

Abbreviations	
ZCES	Zero-carbon Energy System
GB/GG	Gas boiler/Gas generator set
CHP	Combined heating and power
CCHP	Combined cooling, heating and power
EH/EC	Electric heating/Electric cool
HP/AC	Heat pump/Absorption chiller
P2G	Power to gas
DG/ES	Distributed Generation/Energy storage
EnH	Energy hub
Symbols	
$W_{EC} / W_{EE} / W_{EF} / W_{EN}$	Weight factors of each objective
C_{INV} / C_{OPE}	The total investment and operating costs
*	Electricity/gas/heat/cool
&	GB/GG/CHP/CCHP/EH/HP/EC/AC/P2G in EnH
#	EnH;DG;ES
i, j, k, l, m	Refers to the nodes of the energy system
ts	The t hour of the s quarter
n;N	Time period; Total number of time periods in a scheduling cycle
$\Omega_{*L};\Omega_{\#};\Omega_{*sta}$	Set of *line;set of #； Set of * distribution station
$x_{ij}^{*L};x_{k/l/m}^{\#}$	0-1 variable, *line or # whether to build
$C_{ij}^{*L};C_{k/l/m}^{\#}$	Average annual construction cost of *line and #
$BP_i^{*,ts};\lambda_*$	Buy power quantity of *;purchase price of *
Ω_{dr*}	Set of * nodes with demand response potential
$P_i^{dr*,ts}$	Demand response cuts related energy power
μ_{dr*}	* unit incentive coefficient of demand response.
$PG_i^{\&,t}$	The power of the & unit at time t
$\rho_i^{*,t}$	Scaling factor of * unit power and carbon emissions
$LP_i^{*,ts}$	* Energy load power
$P_i^{*,\&,ts}$	Input * power of & equipment
$\eta_i^{\&}$	Energy Conversion Efficiency of & Equipment
$x_{i,\&}^{EnH}$	0-1 variables, & whether to build
$P_i^{\&\max}$	The maximum output power of the devices &
$P_i^{DG\max}$	Maximum active power that the DG can output
$\sigma_i^{DG,ts}$	Output coefficient of DG
$P_i^{ES(in/out),n}$	Net discharge (charge/discharge) power
$SOC_i^{\min/n/\max}$	Stored energy
ε_i^{loss}	Energy loss rate while charging
$P/Q_{ik/ji}^{*,ts}$	Active and reactive power between nodes
$SP/Q_i^{*,ts}$	Active and reactive power injected into nodes in substations
$LP/Q_i^{*,ts}$	Active and reactive loads in nodes
$P_i^{*,ts}$	Active power input to the energy hub
$P_i^{DG,ts}$	Active power injected by DG into nodes
$P/Q_i^{DR,*,ts}$	Demand response cuts active and reactive power

1. INTRODUCTION

Greenhouse gas emissions from cities and towns are a major contributor to climate change, and the heat, floods and rising sea levels etc. which caused by climate change will also impact the development of cities and towns severely[1]. According to UN Habitat, cities and towns consume 78% of the world's energy and produce more than 60% of GHG emissions[2]. Over the coming decades, the urbanization process will necessarily coincide with the urgent need to decarbonize the global energy system[2]. This makes carbon neutral cities development becoming an important concept to addressing climate change [4][5].

China's urbanization ratio hit 64.72% in 2021, Probability of the peak will be 75% to 80% by 2035[6]. China's carbon emissions are mainly determined by the energy sector too. So it is necessary to accelerate clean energy transition[7]. In the context of the superposition of urbanization and energy transformation, it is becoming more and more important to build a zero-carbon energy system for sustainable urban development in china.

At present, some clean energy technologies have been developed relatively maturely, such as wind and solar power generation[8]. Meanwhile, responsiveness, digitization, artificial intelligence, carbon trading, smart grids, and electric vehicles are contributing to low-carbon city[9]. Some studies have analyzed the construction methods of city's energy system, including multi-objective optimization[10][11], sector coupling [12], and scenario-based method[13]. However, the development of energy prosumers (both energy consumers and energy producers, often using solar photovoltaic systems to generate electricity) are reshaping the traditional energy trading relationships and boundaries between energy production and consumption[14][15]. This will affect the architecture of the energy system.

Each region needs a tailored strategy that can optimally utilize its energy potential[9]. This paper describes a construction model of zero-carbon energy system towards carbon-neutral cities based on local produced renewable energy suitable for cities and towns. This model considers the multi-element coordination of source-network-load-storage and the multi-objective coordination of economy, energy and environment fully, considers the constraints of the physical operation constraints of the energy system, the boundary conditions of the diversified energy supply and consumption scenarios, and the multi-factor decision variables. It also analyzes the effects of its application in Dazhangzhuang, located in the core area of Beichen Industry-City,China.

The paper is organized as follows. Section 2 Introduces the Ideas and methods to building the zero-carbon energy system(ZCES). Section 3 introduces the one of the pilot applications—Tianjin smart energy town. Section 4 discusses on further exploration directions for building the ZCES towards carbon-neutral cities.

2. CONSTRUCTION OF ENERGY SYSTEM TOWARDS CARBON-NEUTRAL CITIES

2.1 Modeling ideas

2.1.1 Multi element collaboration

Like the existing energy system, ZCES includes energy production conversion (source), transmission (network), consumption (load), and storage, but it more emphasis on the cleanness of the source, safety of the network, load responsiveness, and storage security. It can ensure the balance of supply and demand of the source and load, and also ensure the safe, economical and reliable operation of network through rapid demand response and planned active adjustment.

As shown in Fig.1. ZCES has many specific elements, and it is also necessary to consider the economic and technical characteristics comprehensively of each factors and make full use of renewable energy according to local conditions. Through the integration of source-grid-load-storage and multi-energy complementary development of electricity-heat-cooling-gas, it can meet the diverse energy needs of different cities and towns.

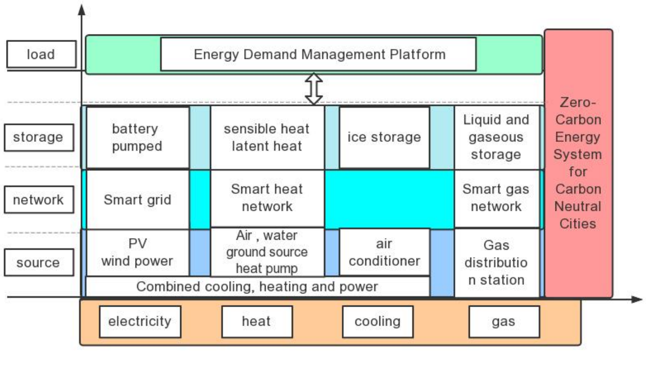

Fig. 1. Element of Energy System towards Carbon-neutral Cities

2.1.2 Multi-objective collaboration

This model is an overall mathematical programming model, and the objective function of which is a coordinated and comprehensive optimization of economic, energy efficiency, electrification rate and environment goals. While seeking comprehensive development, localized development is also taken into account. Among them, the economic goal refers to the minimization of overall investment and operating costs; the energy efficiency goal is to maximize the overall energy efficiency of the system; the electrification rate goal is to maximize the proportion of electric energy in the planned area; the environmental goal is to minimize the overall carbon dioxide emissions.

2.2 Model building

2.2.1 Objective function

The overall objective function of the model is shown in formula (1), and the weight factors of each objective are weighed according to the actual development needs of the planned area.

$$\min F = \min\begin{pmatrix} W_{EC}F_{EC} + W_{EE}F_{EE} + \\ W_{ER}F_{ER} + W_{EN}F_{EN} \end{pmatrix} \tag{1}$$

(1) Economic goal

$$\min F_{EC} = C_{INV} + C_{OPE} \tag{2}$$

$$\begin{aligned} C_{INV} = & \sum_{(i,j)\in\Omega_{EL}} x_{ij}^{EL} C_{ij}^{EL} + \sum_{(i,j)\in\Omega_{GL}} x_{ij}^{GL} C_{ij}^{GL} \\ & + \sum_{(i,j)\in\Omega_{HL}} x_{ij}^{HL} C_{ij}^{HL} + \sum_{k\in\Omega_{EnH}} x_{k}^{EnH} C_{k}^{EnH} \\ & + \sum_{l\in\Omega_{DG}} x_{l}^{DG} C_{l}^{DG} + \sum_{m\in\Omega_{ES}} x_{m}^{ES} C_{m}^{ES} \end{aligned} \tag{3}$$

$$C_{OPE} = \sum_{s}\sum_{t}\begin{pmatrix} \lambda_e \sum_{i\in\Omega_{esta}} BP_i^{E,ts} + \lambda_g \sum_{i\in\Omega_{gsta}} BP_i^{G,ts} + \\ \lambda_h \sum_{i\in\Omega_{hsta}} BP_i^{H,ts} + \mu_{dre} \sum_{i\in\Omega_{dre}} P_i^{dre,ts} + \\ \mu_{drh} \sum_{i\in\Omega_{drh}} P_i^{drh,ts} + \mu_{drc} \sum_{i\in\Omega_{drc}} P_i^{drc,ts} \end{pmatrix} \tag{4}$$

(2) Energy efficiency goal

$$\min F_{EE} = \sum_{i\,\in\,\Omega_{e/g/hsta}} \frac{LP_i^{E,ts} + LP_i^{G,ts} + LP_i^{H,ts} + LP_i^{C,ts}}{BP_i^{E,ts} + BP_i^{G,ts} + BP_i^{H,ts}} \tag{5}$$

(3) Electrification rate goal

$$\min_{i\in\Omega_{e/g/hsta}} F_{ER} = -\frac{BP_i^{E,ts}}{BP_i^{E,ts} + BP_i^{G,ts} + BP_i^{H,ts}} \tag{6}$$

(4) Environment goal

$$\min F_{EN} = \sum_{t}\begin{pmatrix} \rho_{CO_2}^{GB} PG_i^{GB,t} + \rho_{CO_2}^{GG} PG_i^{GG,t} + \\ \rho_{CO_2}^{CHP} PG_i^{CHP,t} + \rho_{CO_2}^{CCHP} PG_i^{CCHP,t} \end{pmatrix} \tag{7}$$

2.2.2 Main constraints

(1) Energy conversion device constraints

1) Energy hub cold, hot and electrical power balance constraints

$$\begin{cases} LP_i^{C,ts} = \eta_i^{EC} P_i^{E,EC,ts} x_{i,EC}^{EnH} \\ \qquad +\eta_i^{AC} P_i^{H,AC,ts} x_{i,AC}^{EnH} \\ \qquad +\eta_i^{CCHP} P_i^{G,CCHP,ts} x_{i,CCHP}^{EnH} \\ LP_i^{H,ts} = \eta_i^{GB} P_i^{G,GB,ts} x_{i,GB}^{EnH} \\ \qquad +\eta_i^{CHP,H} P_i^{G,CHP,ts} x_{i,CHP}^{EnH} \\ \qquad +\eta_i^{CCHP,H} P_i^{G,CCHP,ts} x_{i,CCHP}^{EnH} \\ \qquad +\eta_i^{EH} P_i^{E,EH,ts} x_{i,EH}^{EnH} \\ \qquad +\eta_i^{HP} P_i^{E,HP,ts} x_{i,HP}^{EnH} \\ LP_i^{E,ts} = \eta_i^{GG} P_i^{G,GG,ts} x_{i,GG}^{EnH} \\ \qquad +\eta_i^{CHP,E} P_i^{G,CHP,ts} x_{i,CHP}^{EnH} \\ \qquad +\eta_i^{CCHP,E} P_i^{G,CCHP,ts} x_{i,CCHP}^{EnH} \\ LP_i^{G,ts} = \eta_i^{P2G} P_i^{G,P2G,ts} x_{i,P2G}^{EnH} \\ \qquad i \in \Omega_{EnH} \end{cases} \tag{8}$$

2) Device capacity constraints in the energy hub

$$\begin{cases} 0 \le \eta_i^{GG} P_i^{G,GG,ts} \le P_i^{GG\max} x_{i,GG}^{EnH} \\ 0 \le (\eta_i^{CHP,H} + \eta_i^{CHP,E}) P_i^{G,CHP,ts} \\ \quad \le P_i^{CHP\max} x_{i,CHP}^{EnH} \\ 0 \le (\eta_i^{CCHP,H} + \eta_i^{CCHP,E} + \eta_i^{CCHP,C}) P_i^{G,CCHP,ts} \\ \quad \le P_i^{CCHP\max} x_{i,CCHP}^{EnH} \\ 0 \le \eta_i^{GB} P_i^{G,GB,ts} \le P_i^{GB\max} x_{i,GB}^{EnH} \\ 0 \le \eta_i^{EH} P_i^{E,EH,ts} \le P_i^{EH\max} x_{i,EH}^{EnH} \\ 0 \le \eta_i^{HP} P_i^{E,HP,ts} \le P_i^{HP\max} x_{i,HP}^{EnH} \\ 0 \le \eta_i^{EC} P_i^{E,EC,ts} \le P_i^{EC\max} x_{i,EC}^{EnH} \\ 0 \le \eta_i^{AC} P_i^{H,AC,ts} \le P_i^{AC\max} x_{i,AC}^{EnH} \\ 0 \le \eta_i^{P2G} P_i^{E,P2G,ts} \le P_i^{P2G\max} x_{i,P2G}^{EnH} \\ i \in \Omega_{EnH} \end{cases} \tag{9}$$

3) Distributed power constraints

$$0 \le P_i^{DG,ts} \le \sigma_i^{DG,ts} P_i^{DG\max} x_i^{DG} \tag{10}$$

(2) Energy storage charging and discharging power and state constraints

$$P_i^{ES,n} = P_i^{ESout,n} - P_i^{ESin,n} \tag{11}$$

$$SOC_i^{n+1} = SOC_i^n + \varepsilon_i^{loss} P_i^{ESin,n} - P_i^{ESout,n} \tag{12}$$

$$SOC_i^0 = SOC_i^N \tag{13}$$

$$-P_i^{ES\max} x_i^{ES} \le P_i^{ES,n} \le P_i^{ES\max} x_i^{ES} \tag{14}$$

$$0 \le P_i^{ESin,n} \le P_i^{ES\max} x_i^{ES} \tag{15}$$

$$0 \le P_i^{ESin,n} \le P_i^{ES\max} x_i^{ES} \tag{16}$$

$$SOC_i^{\min} \le SOC_i^n \le SOC_i^{\max} \tag{17}$$

(3)Energy transmission network constraints

1）Electricity distribution network constraints

①Node power balancing constraints

$$\begin{cases} \sum\limits_{(i,j)\in\Omega_{EL}} P_{ji}^{E,ts} + SP_i^{E,ts} + P_i^{DG,ts} = \\ \sum\limits_{(i,k)\in\Omega_{EL}} P_{ik}^{E,ts} + LP_i^{E,ts} + P_i^{E,ts} - P_i^{DR,e,ts} \\ \sum\limits_{(i,j)\in\Omega_{EL}} Q_{ji}^{E,ts} + SQ_i^{E,ts} = \\ \sum\limits_{(i,k)\in\Omega_{EL}} Q_{ik}^{E,ts} + LQ_i^{E,ts} - Q_i^{DR,e,ts} \end{cases} \tag{18}$$

②Distribution line capacity constraints

$$\begin{cases} 0 \le P_{ij}^{E,ts} \le P_{ij}^{E\max} x_{ij}^{EL} \\ 0 \le Q_{ij}^{E,ts} \le Q_{ij}^{E\max} x_{ij}^{EL} \end{cases} \tag{19}$$

③Substation output constraints

$$\begin{cases} 0 \le SP_i^{E,ts} \le SP_i^{E\max} \\ 0 \le SQ_i^{E,ts} \le SQ_i^{E\max} \end{cases} \tag{20}$$

④Demand response constraints

$$\begin{cases} 0 \le P_i^{DR,e,ts} \le (P_i^{DR,e,ts})_{\max} \\ 0 \le Q_i^{DR,e,ts} \le (Q_i^{DR,e,ts})_{\max} \end{cases} \tag{21}$$

2) Gas distribution network constraints

①Node balance bonstraint

$$\sum_{(i,j)\in\Omega_{GL}} P_{ji}^{G,ts} + SP_i^{G,ts} = \sum_{(i,k)\in\Omega_{GL}} P_{ik}^{G,ts} + LP_i^{G,ts} + P_i^{G,ts} \tag{22}$$

②Gas distribution piping capacity constraint

$$0 \le P_{ij}^{G,ts} \le P_{ij}^{G\max} x_{ij}^{GL} \tag{23}$$

③Output constraints of gas distribution station

$$0 \le SP_i^{G,ts} \le SP_i^{G\max} \tag{24}$$

3)Distribution heat network constraints

①Node heat balance constraints

$$\begin{aligned} &\sum_{(i,j)\in\Omega_{HL}} P_{ji}^{H,ts} + SP_i^{H,ts} = \\ &\sum_{(i,k)\in\Omega_{HL}} P_{ik}^{H,ts} + LP_i^{H,ts} + P_i^{H,ts} - P_i^{DR,h,ts} \end{aligned} \tag{25}$$

②Heat distribution pipeline capacity constraints

$$0 \le P_{ij}^{H,ts} \le P_{ij}^{H\max} x_{ij}^{HL} \tag{26}$$

③Output constraint of heat distribution station

$$0 \le SP_i^{H,ts} \le SP_i^{H\max} \tag{27}$$

④Demand response constraints

$$0 \le P_i^{DR,h,ts} \le (P_i^{DR,h,ts})_{\max} \tag{28}$$

The planning mode considers the lowest economic cost, the lowest environmental cost, the highest energy efficiency, and the highest electrification rate comprehensively. It takes diversified energy supply and consumption scenarios as boundary conditions and energy interconnection system elements as decision variables, which can cover and reasonably configure the constituent elements of urban energy systems, and flexibly adapt to different energy supply and consumption scenarios and planning needs. The approximate linearization of the programming model can be efficiently solved by the mixed integer linear method. But the linear weighted model has a certain loss and omission of the original target information. In the specific solution process, it is necessary to carry out a scenario analysis based on the actual situation. It is worthy to note that if the optimal solution cannot be obtained, a compromise solution can be obtained according to the priority of reliable energy, clean and efficient energy, and low energy cost, or the most suitable solution can be selected from multiple feasible solutions through expert evaluation.

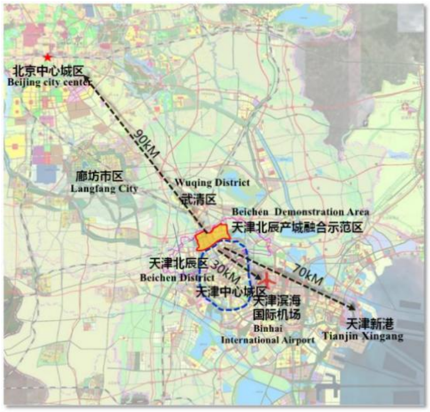

Fig.2. Beichen (Dazhangzhuang) low carbon Town

3. PILOT APPLICATION OF ZERO-CARBON ENERGY TOWARDS CARBON-NEUTRAL CITIES

3.1 Basic information on application case

Dazangzhuang, one of the Smart Energy Town locat in the core area of Beichen Industry-City Integration Demonstration Zone, Tianjin city, China. It is the first batch of industry-city integration demonstration zones at the national level as shown in Fig.2. The town covers an area of 6.4 square kilometers and has a permanent population of 12,000. It had taken the integrated energy system as the main line and carried out the development before. However, it's energy utilization scattered relatively, the contradiction between gas and heat supply is prominent, and the interconnection of production and city and energy supply network needs to be strengthened; the multi-energy data collection and information transmission are separated from each other, and the degree of energy information integration needs to be further improved; the complementary utilization of resources is insufficient, and the comprehensive energy efficiency is low.

3.2 *Application ideas and basic results*

State Grid Tianjin Electric Power Company had undertaken the construction of Beichen Dazhangzhuang Smart Clean Energy Town. The town was adopted the ZCES model described in this paper for the planning and construction of the town's energy system. It considers multi-objective coordination optimization in planning, opens up the key links of source-network-load-storage, and realizes the complementary coordination of electricity- heat-cooling-gas. Specifically, the town fully utilizes clean energy resources, exerts synergistic ideas in the aspects of terminal building intelligence, regional energy supply interconnection, multi-energy information integration, intensive production and town management and control, and improves energy efficiency and cleanliness .

After applying the energy system constructed above in the case. The town has access to 11 kinds of scene data information, such as photovoltaic, ground source heat pump, distributed energy storage, mobile energy storage, AC / DC microgrid, cold and thermal power energy station, residential users, enterprise users, phase change heat storage, charging facilities, power grid data and so on. Among them, there are 22 enterprise users, 344 resident users, and 1775 sets of various transformation meters, and the proportion of regional electric energy in terminal energy reaches 46.4%.

The town achieved the goals of energy saving, emission reduction, and low carbonization, and laid the foundation of the energy system for the town to achieve carbon neutrality. In the future, the Dazhangzhuang should transform their business methods to contribute to carbon neutrality in the following ways. For example, to further increase the electrification rate. At the same time, further explore the innovative and leading role of new technologies such as 5G and artificial intelligence in smart energy supply and develop new models of low-carbon energy utilization.

4. FURTHER DISCUSSION

The ZCES is an energy system for carbon neutral towns. To achieve carbon neutrality in towns, further actions should be taken in the following four areas.

Firstly,the ZCES needs to adapt to local conditions and maximize the use of clean energy inside and outside the cities. Based on the concepts of clean energy substitution and re-electrification, the terminal demand of each energy category is analyzed, and the local energy resource conditions (such as wind power, PV, ground source heat pump, urban wastewater and waste heat) and available energy resources are taken into consideration in combination with the current and future demand conditions. The external resources obtained through the large power grid and other channels are optimized and balanced to maximize the use of clean energy. Distributed renewable energy power generation/heating, small-combined cooling, heating and power, small geothermal, urban wastewater, urban waste heat, P2G, V2G, heat storage/cooling/gas storage/electricity storage, smart home, smart building, charging Various elements such as piles are organically combined to realize on-demand conversion and coordination among various forms of clean energy in the network.

Secondly,the ZCES should be user-centered internally to ensure the balance of energy supply and demand for users. When energy prosumers enter the market, they need to fully stimulate new formats, models and applications. When designing the energy system, we should link market-oriented, customer-centric, gather a wide range of participants, and fully consider the integration of big data, blockchain, artificial intelligence and other technical means to form an urban energy business ecosystem. The system covers the entire chain of energy production, collection, storage, transmission, transaction, and utilization, including system optimization and operation and maintenance, comprehensive solution provision, data management, application development, financial services and other key formats.

Thirdly,the ZCES should be integrated deeply with the outside world. ZCES make full use of internet collaborative innovation ideas, share data and innovation, and link global partners and stakeholders, energy system construction and operation institutions, industry-university-research institutions, third-party service providers and application development institutions, etc., in the aim to better achieve a variety of cleanliness, complementary utilization of energy, and coordinated response of source, grid, load, and storage. Develop integrated planning, including integration of physical information, integration of energy and transportation, and integration of energy supply and demand. Consider new interactive energy-consuming equipment, demand response and other ways to participate in large-scale system scheduling and operation, and consider their potential to participate in system power balance, peak regulation and frequency regulation, and backup.

Finally, ZCES also need to be integrated with sustainable urban development. Let the energy system organically integrate with the cities clean production, transportation, buildings, and residents' life. Guarantee the security of clean energy supply and improve the ecological quality and development efficiency and reshape the social low-carbon consumption and life concept.

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