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Integrated Energy System Modeling of China for 2020 by Incorporating Demand Response, Heat Pump and Thermal Storage

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ABSTRACT Electricity and heat energy carriers are mostly produced by the fossil fuel sources that are conventionally operated independently, but these carriers have low efficiency due to heat losses. Moreover, a high share of variable renewable energy sources disrupts the power system reliability and flexibility. Therefore, the coupling of multiple energy carriers is underlined to address the above-mentioned issues that are supported by the latest technologies, such as combined heat and power, heat pumps, demand response, and energy storages. These coupling nodes in energy hubs stimulate the conversion of the electric power system into the integrated energy system that proves to be cost-effective, flexible, and carbon-free. The proposed work uses EnergyPLAN to model electricity, district, and individual heating integrated energy system of China for the year 2020. Furthermore, the addition of heat pumps, thermal storage, and demand response is analyzed in different scenarios to minimize the annual costs, fuel consumption, and CO_2 emissions. Technical simulation strategy is conducted for optimal operation of production components that result in the reduction of the above-mentioned prominent factors while calculating the critical and exportable excess electricity production. The simulation results demonstrate that demand response and thermal storage significantly enhance the share of variable renewable energy sources. In addition, it substantially reduces the annual costs and fuel consumption, while heat pump increases the system efficiency.

INDEX TERMS Demand response, district heating, energy hub, EnergyPLAN, energy storage, integrated energy system, multiple energy carriers, variable renewable energy sources.

I. INTRODUCTION

With the rapid development of industrialization and urbanization, electricity is not the only energy consumed by users but they also need heating, cooling and natural gas for daily life activities. However, conventional energy infrastructures like electricity and heat deal independently that makes the system less robust and low efficient with high operational cost [1], [2]. Consequently, Multiple Energy Carries (MEC) integration mitigate these challenges because different sources can back up each other in case of contingency that enhances system sustainability, flexibility and reliability [3], [4]. Coupling of MEC is known as Integrated Energy System (IES) and among all IESs, Combine Heat and Power (CHP) integration with electricity network has gained spectacular growth to fulfill users electric and heat demands with minimum emission [5]. Moreover, IES also helps in boosting the economy of energy systems by increasing energy efficiency, decreasing fuel consumption, and deferring the electric network expansion. Furthermore, the flexibility of the system is improved that plays a vital role in integrating more Variable Renewable Energy Sources (VRES), like wind and solar Photo Voltaic (PV), by eliminating the uncertainty and variability issues [6]–[8]. This will make inroads to achieve a carbon-free environment by decreasing dependency on fossil fuels that become indispensable for China which is the world's biggest energy consumer and largest CO_2 emitter [9]–[11]. Heat infrastructure is divided into Individual

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Heating (IH) and District Heating (DH) network. The district heating network of China is the world's second-biggest grid that contributes significantly in polluting the environment [12], [13]. The Chinese government is focusing on MEC integration and pilot projects like active distribution network in Jiaxing City and Shanghai tower are a typical example of the integration of electrical, thermal and gas energy. Minimum 15% share for renewable energy to its overall consumption by 2020 [14] and becoming the biggest Renewable Energy Source (RES) investor by 2030 are the main energy goals of China [15], [16]. Additional flexibility on demand side in the form of Demand Response (DR), Electricity Storage (ES) and Thermal Storage (TS) are influential factors for two biggest energy sectors (electricity and heat) to achieve successful and economic integration of MEC. The excess energy in case of abundant RES generation can be either sold to the grid or stored in TS and ES systems and reused later. Additionally, electrifying the heating by technologies like Heat Pump (HP) is an effective method of lowering carbon footprint [17].

It is recommended to use MEC within the context of energy hub to enable collaboration among energy carriers. The energy hub approach was first proposed by a research team at Power Systems and High Voltage Laboratory within the framework of a project called "a vision of future energy networks" [18]. This supernode energy hub of MEC facilitates the integration of Distributed Energy Resources (DER) like RES, DR, ES and TS in order to minimize the operation costs [19]. In consequence, energy hub becomes a subject of interest to achieve optimal management of MEC.

Optimal placement of a heat pump in an integrated power and heat energy system is carried out by [20] that helps to minimize electric and heating utilities investments. Heat pump and CHP based integrated energy system is analyzed by [21] to minimize heat loss. Wanjiru *et al.* [22] propose heat pump optimal control strategy with renewable energy to improve energy efficiency. Smith *et al.* [23] investigated thermal energy storage benefits when combined with CHP. Thermal energy storage role on increasing system flexibility, providing ancillary services and mitigating the effect of variable renewable energy sources are discussed by [24]

Role of DR in integrating DER is addressed in [25], RES integration with DR using EnergyPLAN while employing Vehicle-to-Grid (V2G) technology to exploit synergies between sectors is carried out in [26]. Wu *et al.* [27] propose smart dispatch for IES to enable DR that helps in integrating more VRES. Previously, few of the case studies in China municipalities like Chongming [28], Beijing [29] and Jiangsu province [30] are analyzed with EnergyPLAN model. Nevertheless, above sub-systems infrastructures are not completely analyzed on large IES model. Besides, modeling IES in software while including renewable energy sources and storages may increase the electricity production more than transmission line capacity which is termed as Critical Excess Electricity Production (CEEP). This surplus electricity production including critical and exportable excess is mostly overlooked and technologies like large-scale HPs in MEC are not taken into account outside Europe. In order to bridge the gap, this research aims to be a first study of such a large IES planning of China. As it involves multiple storages (ES and TS), HPs and DR that eases out VRES integration, improves system flexibility and enhances energy efficiency. The main contributions of this work are:

i) Electricity and heat infrastructure data for the year 2020 is collected to model China IES using Smart Energy Hub (SEH) in EnergyPLAN. Further, the IES model is holistically investigated to determine annual costs, total fuel consumption, RES share, Critical Excess Electricity Production (CEEP) and Exportable Excess Electricity Production (EEEP).

ii) Technical simulation strategy is performed to adjust production components in such a way that reduce Primary Energy Supply (PES) or fuel consumption, CO_2 emissions and total costs. Multiple scenarios such as integrating more VRES, replacement of boilers by HPs in IH network, the addition of TS and DR are developed to signify its effect on objective functions of IES.

This paper is organized as follows: Section 2 explains the proposed SEH approach and presents mathematical modeling for IES analysis. Data simulation required to model IES is presented in section 3. Different scenarios and simulation results are discussed in section 4. Finally, conclusions are summarized in section 5.

II. PROPOSED SMART ENERGY HUB

Energy hub is the interfacing hub among energy providers, aggregators, users, and corresponding power carriers subnetworks that is used to produce, convert, store and distribute MEC to fulfill energy demands. EnergyPLAN is designed in such a way so that smart grids coordination, RES utilization and conversion to other carriers is possible which makes a smart energy system to attain higher efficiency with lesser emission. Smart energy hub approach is used for MEC modeling that contains electrical, DH and IH network of China by the year 2020 is presented in Figure 1. Electricity demand is met by RES sources (hydropower, wind, solar PV and geothermal), Nuclear Power Plants (NPP), Thermal Power Plants (TPP) and CHP. DH demand is fulfilled by CHP and boilers while HPs and boilers are used to meet IH demand. In this work, hydropower, NPP and geothermal supply do not vary unlike VRES to optimize objective functions.

A. MATHEMATICAL MODELING

1) INPUTS AND OUTPUTS

Fossil fuel power plants are less efficient as 2/3 energy is wasted in the form of heat but DER sources generated near consumer premises can solve this problem. It reduces distribution and transmission losses, cut down energy costs and results in higher efficiency. Controlled RES (Hydropower and geothermal), VRES (Wind and Solar), NPP and condensing power plants (TPP and CHP plants that uses coal or Ngas) serve as the inputs to produce the required heat and electricity outputs.

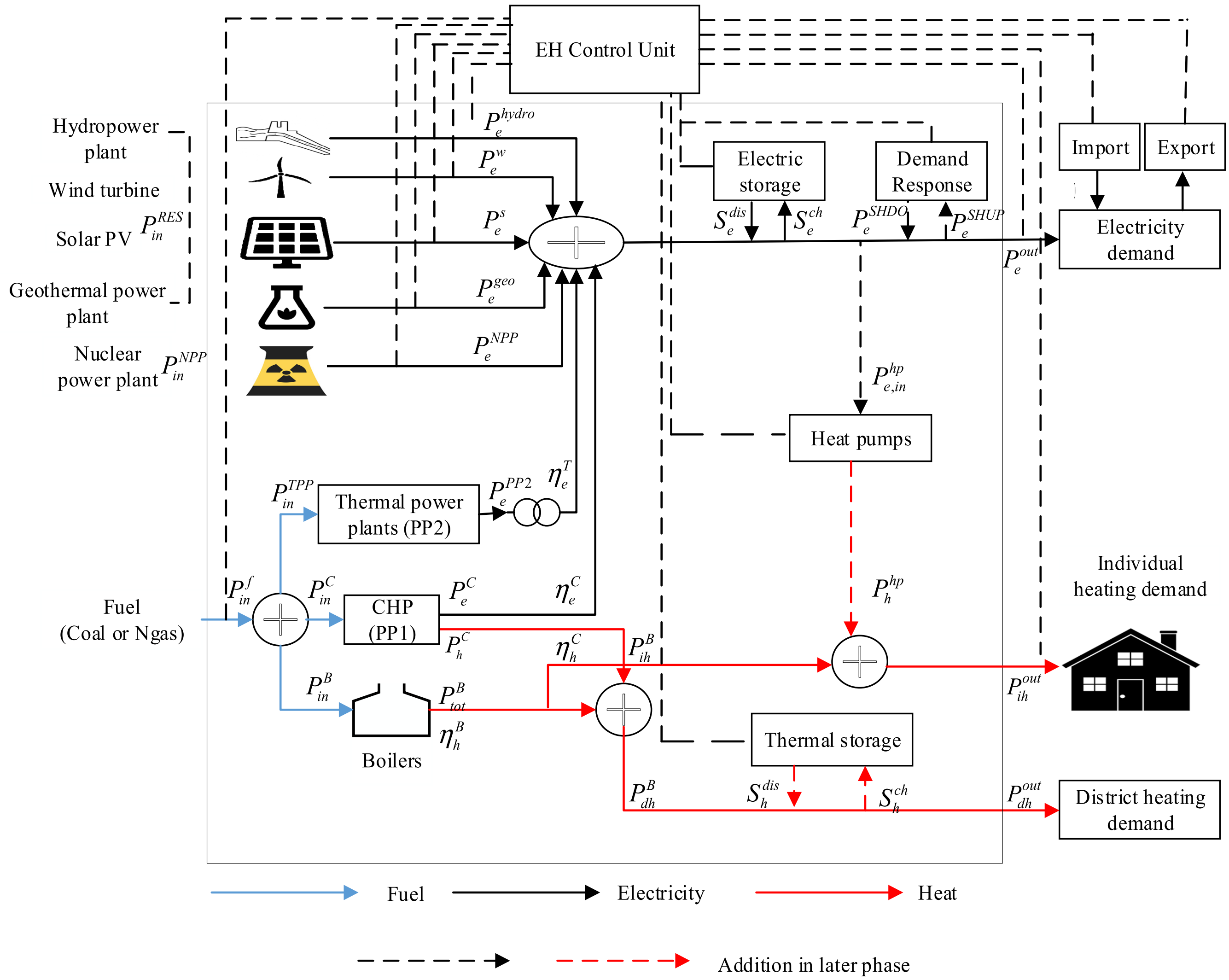

FIGURE 1. **Proposed smart energy hub.**

Total power generated is given by equation 1.

$$P^{tot} = P_e^{out} + P_h^{out} \tag{1}$$

Electricity and heating demand during whole specified 2020 year of 366 days remain fixed as elaborated in equations 2 and 3

$$P_e^d = \sum_{t=1}^{8784} P_{e,t}^{out} \tag{2}$$

$$P_h^d = \sum_{t=1}^{8784} P_{h,t}^{out} \tag{3}$$

Heat supply is divided into District Heating (DH) and Individual Heating (IH) network as deduced in equation 4.

$$P_h^{out} = P_{dh}^{out} + P_{ih}^{out} \tag{4}$$

Total electricity generated by proposed SHE is given as

$$P_e^{out} = v(\eta_e^T \times P_e^{pp2}) + (1-v)(\eta_e^C \times P_{in}^C) + P_e^{RES*} \ldots \\ \ldots + P_e^{NPP} + P_e^{SHDO} - P_e^{SHUP} + S_e^{dis} - S_e^{ch} - P_{e,in}^{hp} \tag{5}$$

where, P_e^{SHDO}, P_e^{SHUP} represents total shift down and shift up power from peak hours to valley hours while total power that flows into converters is represented by dispatch factor, v.

The power generated by NPP and RES are presented in equations 6-14 [31].

$$P_e^{NPP} = \frac{\eta_e^{NPP} \times f^{NPP} \times CF^{NPP} \times P_{in}^{NPP} \times d^{NPP}}{Max(d^{NPP})} \tag{6}$$

where, f represents total amount of fuel and d shows energy production distribution between 8784 values.

Power generated by RES such as wind, solar, hydro and geothermal is shown in equation 7.

$$P_e^{RES*} = P_e^w + P_e^s + P_e^{hydro} + P_e^{geo} \tag{11}$$

$$P_e^w = P_{in}^w \times 8784 \times C.F^w \tag{12}$$

Electricity production from VRES like wind and solar can be computed by multiplying capacity with hourly distribution. Nonetheless, different configurations may lead to higher or lower production. Consequently, Correction Factor (C.F.) can vary the distribution and enhance

TABLE 1. Complete list of converters used in proposed SEH.

Converter Type	Name	Description	Equation
Single input, Single output	Boiler	It generates heat by using gas supply and its output is given in equation 19.	$P_{tot}^{B} = \eta_{h}^{B} \times P_{in}^{B}$ (19)
Single input, multiple outputs	CHP	It uses only input (fuel) to generate multiple outputs (electricity and heat).	$P_{e}^{C} = \eta_{e}^{C} \times P_{e}^{in}$ (20) $P_{h}^{C} = \eta_{h}^{C} \times P_{in}^{C}$ (21)
Single input, single output	Heat Pumps	HP uses electricity to generate heating in individual heating network.	$P_{h}^{hp} = COP^{hp} \times P_{e,in}^{hp}$ (22)

annual production. It depends on the capacity factor (C) and can be computed as:

$$C.F^{w} = \frac{P_{e}^{w}}{C^{w} \times 8784} \tag{13}$$

$$P_{e}^{s} = P_{in}^{s} \times 8784 \times C.F^{s} \tag{14}$$

$$C.F^{s} = \frac{P_{e}^{s}}{C^{s} \times 8784} \tag{15}$$

$$P_{e}^{hydro} = \frac{\eta_{e}^{hydro} \times W^{hydro}}{8784} \tag{16}$$

$$P_{e}^{hydro(ann)} = \eta_{e}^{hydro} \times W^{hydro} \tag{17}$$

$$P_{e}^{geo} = \frac{\eta_{e}^{geo} \times f^{geo} \times CF^{geo} \times P_{in}^{geo} \times d^{geo}}{Max(d^{geo})} \tag{18}$$

Total amount of heat generated by boilers in represented by P_{tot}^{B} and then this amount is divided to supply for district and individual heating networks.

$$P_{tot}^{B} = P_{dh}^{B} + P_{ih}^{B} \tag{19}$$

DH and IH generated by proposed SEH are computed by equations 16 and 17.

$$P_{dh}^{out} = v(\eta_{h}^{C} \times P_{in}^{C}) + (1 - v)(\eta_{h}^{B} \times P_{dh}^{B}) + S_{h}^{dis} - S_{h}^{ch} \tag{20}$$

$$P_{ih}^{out} = (\eta_{h}^{B} \times P_{ih}^{B}) + (COP^{hp} \times P_{e,in}^{hp}) \tag{21}$$

Fuel input is split into two converters for electricity (TPP and CHP) and heat (CHP and boilers) infrastructures. As a result, dispatch factor represented by v is introduced that represents the amount of power flows into converters. Its value lies within 0 and 1 and the sum of dispatch factors will always be equal to one. The mapping of the aforementioned input-output carriers established by SEH can be formulated in matrix form as depicted in equation 18.

$$\underbrace{\begin{bmatrix} P_{e}^{out} + S_{e}^{dis}/\eta_{e}^{dis} \\ P_{dh}^{out} + S_{h}^{dis}/\eta_{h}^{dis} \\ P_{ih}^{out} \end{bmatrix}}_{Output\ Matrix} = \underbrace{\begin{bmatrix} \eta_{T}^{e} & \eta_{e}^{C} & 1 & 1 \\ 0 & v\eta_{h}^{C} + (1-v)\eta_{h}^{B} & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}}_{Conversion\ Matrix} \times \underbrace{\begin{bmatrix} P_{in}^{f} \\ P_{in}^{TPP} \\ P_{in}^{NPP} \\ P_{in}^{RES} \end{bmatrix}}_{Input\ Matrix} \tag{22}$$

The converter value lies between 0 and 1, satisfies the law of conservation of energy that output is always less than or equal to input.

2) CONVERTERS

Few sources of SEH inputs do not need to be converted while others may pass through a conversion process before being used as electricity and heating. Converters can be classified according to the number of inputs and outputs. Table 1 outlines the details of converters used in this work.

3) STORAGE

Smart energy hubs may comprise multiple storage elements that can be connected anywhere to inputs, outputs or between converters connecting inputs and outputs. Proposed SEH used both electric and thermal storages and has been connected to the SEH output side. Charging and discharging of electric and thermal storages are elaborated by Equation 23.

$$S_{xs}^{t+1} = S_{xs}^{t}(1 - \delta_{xs}) + \left[P_{x,ch}^{total}\eta_{x,ch} - \frac{P_{x,dis}^{total}}{\eta_{x,dis}} \right] \Delta t \tag{23}$$

where, subscript x represents the type of energy which in this paper is electric (e)or heat energy (h) and δ_{xs} limns the loss of energy during charging.

4) DEMAND RESPONSE FORMULATION

In this work, demand response is introduced in the form of load shifting and assumed to be 10 % of the total electricity demand. It can be quantified by demand price elasticity that is defined as the ratio of change in demand to the ratio of change in price and is calculated by below equation [32]:

$$E = \frac{\frac{\partial P^{d}}{P_{o}^{d}}}{\frac{\partial \lambda}{\lambda}} = \frac{\partial P^{d}}{P_{o}^{d}} \times \frac{\lambda}{\partial \lambda} = \frac{\lambda}{P_{o}^{d}} \times \frac{\partial P^{d}}{\partial \lambda} \tag{24}$$

B. CONSTRAINTS

Total input power should be equal to total output power.

$$P_{in}^{TPP} + P_{in}^{C} + P_{in}^{B} + P_{in}^{NPP} + P_{in}^{RES} = P_{e}^{out} + P_{dh}^{out} + P_{ih}^{out} \tag{25}$$

Total electricity and heating demands during one day remain fixed and should be within their maximum and minimum limits as shown in equations 26 and 27.

$$P_e^{d^{(\min)}} \leq P_e^{out} \leq P_e^{d^{(\max)}} \tag{26}$$
$$P_h^{d^{(\min)}} \leq P_h^{out} \leq P_h^{d^{(\max)}} \tag{27}$$

i) Electric power balance

$$P_e^{pp2} + P_e^C + P_e^{NPP} + P_e^{RES} + S_e^{dis} = S_e^{ch} + P_e^{out} \tag{28}$$

ii) DH network balance

$$P_h^C + P_{dh}^B + S_h^{dis} = S_h^{ch} + P_{dh}^{out} \tag{29}$$

iii) IH network balance

$$P_{ih}^B + P_h^{hp} = P_{ih}^{out} \tag{30}$$

iv) Boiler output constraints

$$0 \leq P_{tot}^B \leq P_{\max}^B \tag{31}$$

v) CHP ramp constraints

$$-R^C \times dt \leq P_t^C - P_{(t-1)}^C \leq R^C \times dt \tag{32}$$
$$P_{\min_c}^C \leq P_c^C \leq P_{\max_c}^C \tag{33}$$

vi) DR

The total amount of power shifted from peak hours (shift up, SHUP) to valley hours (shift down, SHDO) remains the same.

$$\sum_{t=1}^{8784} P_{e,t}^{SHDO} = \sum_{t=1}^{8784} P_{e,t}^{SHUP} \tag{34}$$

Binary variables of shifting up (μ_e^{SHUP}) and shifting down (μ_e^{SHDO}) makes sure that two operations cannot occur simultaneously.

$$0 \leq \mu_e^{SHUP} + \mu_e^{SHDO} \leq 1 \tag{35}$$

vii) Storages

Charging and discharging power limitations are shown in Equations 35 and 36. Binary variable (μ_x), has been introduced which makes sure that charging and discharging cannot occur simultaneously.

$$0 \leq P_{x,ch}^{total} \leq \mu_x P_{x,ch}^{\max} \tag{36}$$
$$0 \leq P_{x,dis}^{total} \leq (1-\mu_x) P_{x,dis}^{\max} \tag{37}$$

Electricity and thermal storages are used in this work, therefore x used in above equations represents electricity and heat energy.

Maximum and minimum energy stored are:

$$En_x^{\min} \leq En_x^t \leq En_x^{\max} \tag{38}$$

III. DATA SIMULATION FOR CHINA 2020

EnergyPLAN uses was developed by Henrik Lund in 1999 and until now extended into 14 versions [33]. It uses Delphi Pascal (DP) programming which is a combination of object oriented programming and integrated development environment. In this tool, technical and market economic energy system analysis at the national or regional level is performed in hourly resolution for the specified year. This freeware software has been extensively used in previous studies including small scale CHP implementation [34], [35], finding optimal size of RES [36]–[38], developing 100% renewable energy system at the national level [39]–[42] and for island [43], [44].

The composite IES analysis using 13.2 version of EnergyPLAN is carried out in hourly steps for the year 2020. MEC comprehensive modeling in this energy balancing tool requires input data set that contains energy demands (electricity and heat), RES sources, conversion units' parameters detail, storage units' limitations and cost data set (annual costs of each production unit, lifetime and percentage of investment). Energy demand forecasting is always hard to predict due to tremendously increasing population, economy and many other factors [45]. Many researchers and organizations predicted future energy demands by considering a lot of assumptions based on different scenario investigation [46]. As far as, electricity demand in this work in considered, it is estimated by considering 1.5% annually increased rate and from 2014-2030 International Energy Agency (IEA) also proposed this national energy demand rate for China [47]. Further, many state-owned websites [48], [49], China energy yearbook [50], State Grid Corporation of China and China power industry statistics [51] are used to collect initial data. Average, maximum, minimum and total energy demands distributed annually for each month are illustrated in Figure 2.

A. ELECTRICITY NETWORK

Total electricity and electric heating demand for the year 2020 is 8034 and 116 terawatt-hours per year (TWh/year) respectively. Wind, PV, NPP, TPP (also mentioned as PP2 in EnergyPLAN), Geothermal, Hydro, back pressure mode CHP, condensing mode CHP (represented as PP) and industrial CHP (CSHP) are used to meet electricity demand and each production components capacity over the whole year is elaborated in Figure 3.

Aforementioned production components capacities and efficiencies used throughout this research is listed in table 2.

B. HEATING NETWORK

The heating network is divided into DH and IH and annual energy demands for both are 1216.46 TWh/year.

1) IH NETWORK

Individual heating demand for reference model is first met by coal and Ngas boilers then for later scenarios, Ngas boilers are replaced with heat pumps that are discussed in section

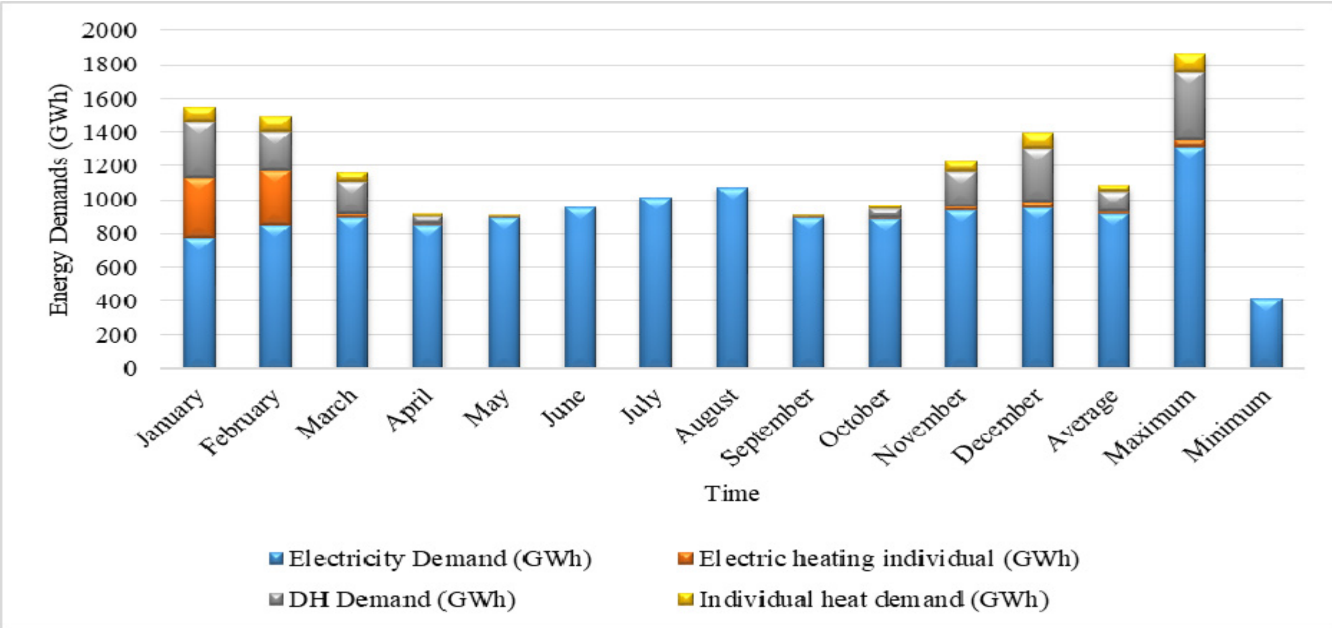

FIGURE 2. Energy demand for the year 2020.

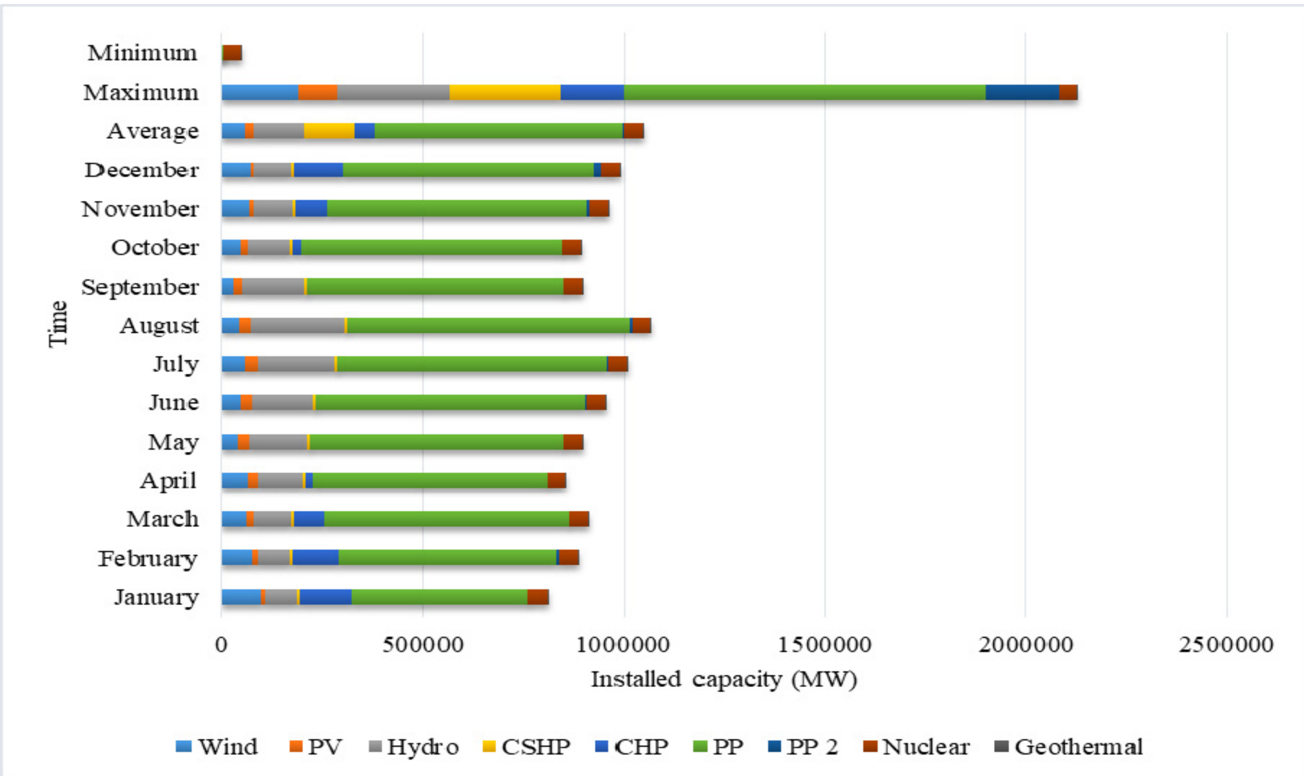

FIGURE 3. Electrical production components capacity in MW.

4. In comparison to IH, DH is economical and technically optimal because IH network consumes more energy which is mostly generated by TPP [11].

2) DH NETWORK

District heating supply in deterministic EnergyPLAN tool is divided into three groups: group 1 demand is met exclusively

TABLE 2. **Electric producing components specifications.**

Source	Capacity (MW)		Efficiency		Correction Factor
CHP 3, PP [*1] (condensing mode operation)	9000000		0.4		--
CHP 3 (back pressure mode operation)[*2]	210000		0.33		
Condensing PP2[*3]	300000		0.4		--
Nuclear	58000		0.36		0.786
Geothermal	1000		1		0.6
Dammed Hydropower	350000		1		--
Wind	200000		--		0.36
Photo Voltaic	100000		--		0.15
Electricity storage	S_e^{ch}	S_e^{dis}	η_e^{ch}	η_e^{dis}	--
	17911	17911	0.8	0.9	--

[*1] PP shows electric capacity of CHP in group 3. [*2] In this mode, CHP generates maximum amount of heat. [*3] Represents electric capacity of thermal power plants also known as condensing power plants

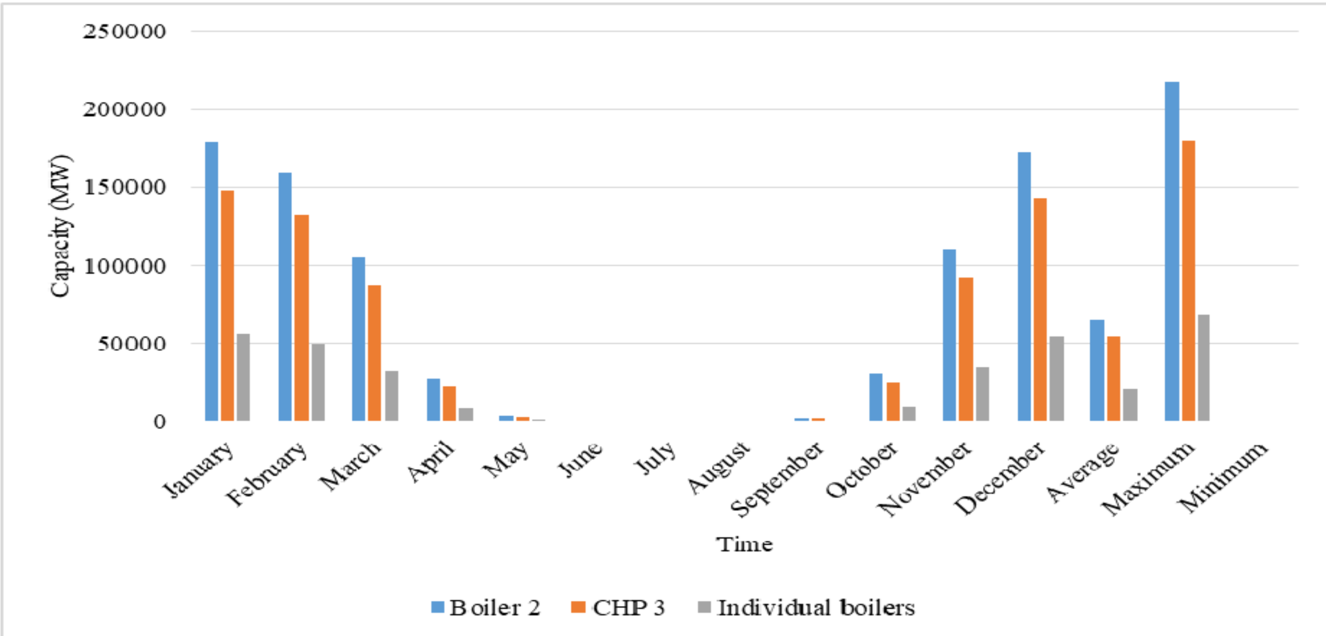

FIGURE 4. **Heat production components capacity in MW.**

TABLE 3. **IH producing components specifications.**

Boiler type	Fuel input (Wh)	Thermal efficiency	Heat demand (TWh/year)
Coal boiler	285	0.35	99.75
Ngas boiler	92	0.88	80.96

by boilers. Group 2 specify DH system with boilers and small CHP plants while group 3 depicts boilers with large extraction CHP plants. Back pressure mode operation of CHP2 can generate electricity and heat at a fixed ratio. However, group 3 CHP can produce electricity alone (condensing mode operation) and also has the ability to produce electricity as well as heat (back pressure mode operation). Therefore, group 3 provides greater flexibility than group 2. In addition, there is also industrial CHP (CSHP) that used only in case of excess electricity production which generates district heating by waste incineration and industry. Consequently, this research uses group 2 boilers and group 3 CHP units to fulfill DH demand. Complete specifications of all district and individual heat producing components are presented in Figure 4 and table 4.

3) COSTS

EnergyPLAN also requires costs analysis consists of production component cost which is measured in Million Renminbi (MRMB) (1 US dollar = 6.77 RMB), lifetime and investment percentage per unit which are presented in table 5.

TABLE 4. DH producing components specification.

Groups	Heat demand (TWh/year)		Boilers (B2) (MW)		CHP (CHP3, PP1) (MW)		Thermal Storage
	Production	losses	P_{in}^{B} (MJ/s)	η_h^B	P_{in}^{C} (MJ/s)	η_h^C	Storage capacity
Group 2	577	0.15	266067	0.62	0	0	--
Group 3	477	0.1	0	0	241818	0.38	600 GWh

TABLE 5. Cost of each component in SEH.

Source	MRMB pr. unit	Years	% of Investment
Large CHP units	0.82	25	3.66
Boilers	0.1	35	3.7
Electric Boilers	0.075	20	1.5
Large power plants	1	27	3
Nuclear	3.6	30	2.5
Pump and turbine	0.6	50	1.5
Pump storage	7.5	50	1.5
Wind	1.3	20	3
Photo voltaic	1.3	30	2.1
Hydro power	3.3	50	2
Geothermal Electr.	2.7	20	3.5
Individual boilers	6.1	21	1.8
Individual HP	14	20	1
Individual electric heat	8	30	1
TS	3	20	7.4
Smart grid costs	400	2	20

IV. SCENARIOS DEVELOPMENT AND RESULTS SIMULATION

The research is divided into 5 scenarios to perform technical analysis against two different simulation strategies for IES analysis. Multiple scenarios development are summarized in table 6.

A. TECHNICAL SIMULATION STRATEGIES

Simulation and operation of every production unit are defined to find the least fuel consuming option. Total costs, fuel consumption, Million tons (Mt) of CO_2, RES share, critical and exportable excess electricity production are determined in simulation strategies as demonstrated in below section.

1) SIMULATION STRATEGY 1 – BALANCING HEAT DEMANDS

In this strategy, the sole focus of all heat production components including CHP generates in consonance with heat demand. CHP units do not need to operate according to fluctuations in VRES. The objective functions for all 5 scenarios are calculated using this strategy.

2) SIMULATION STRATEGY 2 – BALANCING BOTH HEAT AND ELECTRICITY DEMANDS

The prime focus of this strategy for all production components including CHP is to generate both heat and electricity. Moreover, the export of electricity is reduced by using heat pumps that increase electricity demand while decreases electricity production capabilities. In response, the production of condensation plants can be minimized by raising CHP production units' generation.

B. SCENARIO 1 – REFERENCE MODEL

This scenario is considered as a reference model that calculates objective functions (annual costs, PES, Mt CO_2), RES share, CEEP and EEEP by using all of the estimated data for integrated energy planning of China 2020 as shown in Figure 5.

Both critical and exportable excess electricity production is zero as demonstrated in Figure 5. Annual costs are determined in billion Chinese yuan currency (GRMB), fuel consumption in TWh/year while emissions are calculated in Million tons (Mt) of CO_2.

C. SCENARIO 2 – INCREASING VRES SHARE

In this scenario, VRES share is incremented unless CEEP exceeds beyond zero while condensing power plants share decline unless it does not fall below the necessary stabilizing units.

It can be observed in Figure 6 that increasing VRES share decrease annual costs from 1062 GRMB to 1053 GRMB, fuel consumption from 36540 to 35285 TWh.year and CO_2 emissions from 10542 to 9852 Mt in comparison to scenario 1 for simulation strategy 1. Likewise, simulation strategy 2 also slightly decreases all the objective functions in comparisons to strategy 1 by maintaining CEEP to zero. Though there is a small difference in the results of two simulation strategies for objective functions but strategy 2 plays a vital role in incrementing EEEP. The exportable excess electricity production is increased more than 2 TWh/year in comparison to scenario 1 and it will play a similar role for the rest of the scenarios. However, it also increases CEEP more than one.

D. SCENARIO 3 – HP INCLUSION

This scenario increases the use of HP for heating because they are more efficient and environmental friendly than fossil

TABLE 6. Summary of different scenarios development.

Different scenarios	Electricity Network including RES			DH network			IH network		
	Elec. producing components*1	ES	DR	Boilers	CHP	TS	Ngas boilers	Coal boilers	HPs
Scenario 1	√	√	×	√	√	×	√	√	×
Scenario 2*2	√	√	×	√	√	×	√	√	×
Scenario 3	√	√	×	√	√	×	×	√	√
Scenario 4	√	√	×	√	√	√	×	√	√
Scenario 5	√	√	√	√	√	√	×	√	√

*1Electricity producing components include TPP, NPP, Geothermal, Hydro, Wind, PV and CHP *2This scenario only increases VRES share and decreases TPP share.

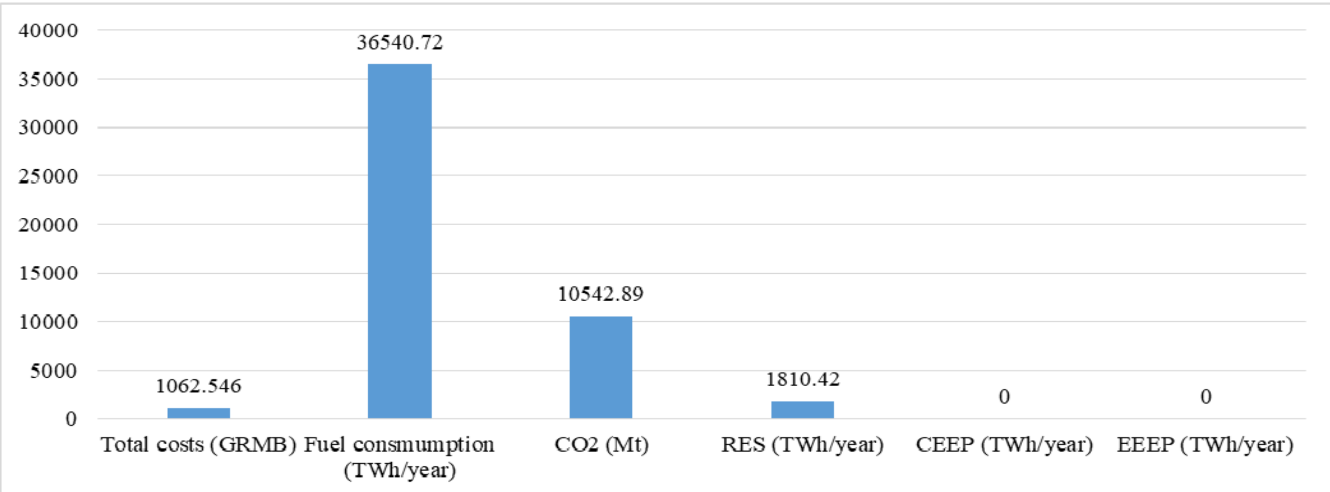

FIGURE 5. Summary performance of reference model (Scenario 1).

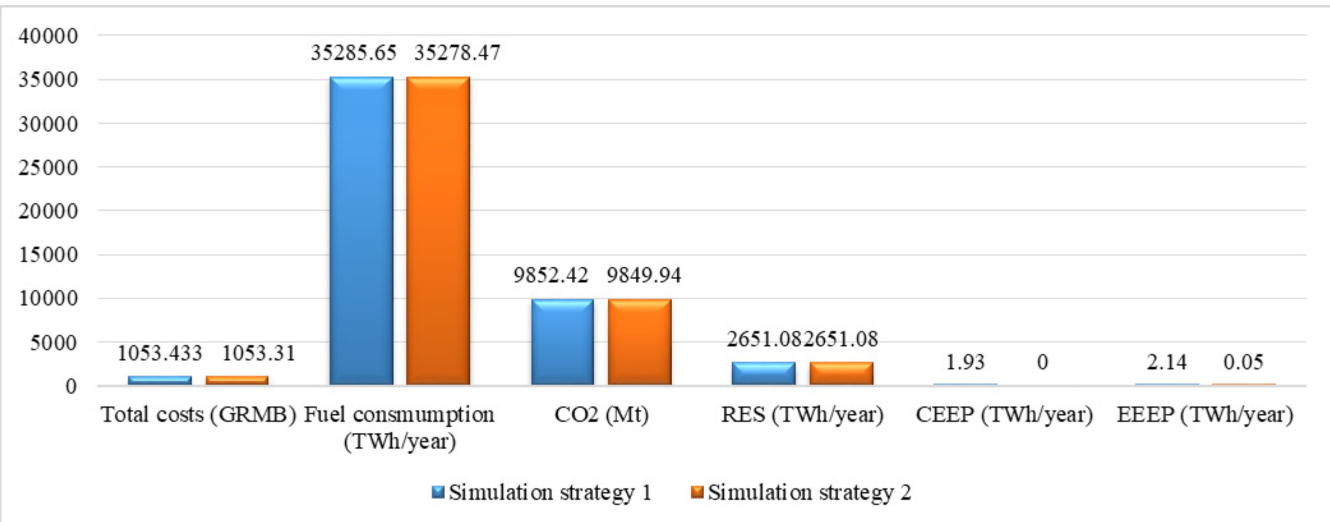

FIGURE 6. Summary performance of integrating more VRES against 2 simulation strategies (Scenario 2).

fuel boilers. Electrification by HP reduces approximately 52% of the emissions in G7 countries [52]. Replacing the natural gas boilers with heat pumps in a case study of Portugal reduces a significant proportion of primary energy and Mt CO_2 emissions [53]. In this work, Ngas boilers are replaced with HP while coal boilers share are also reduced IH network

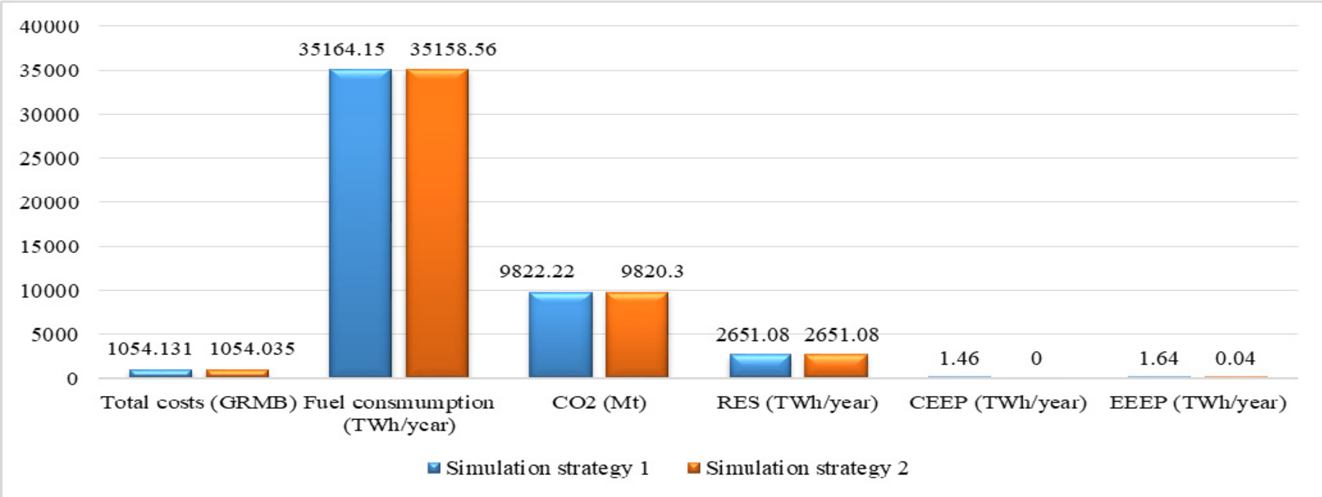

FIGURE 7. Summary performance of adding HP (Scenario 3).

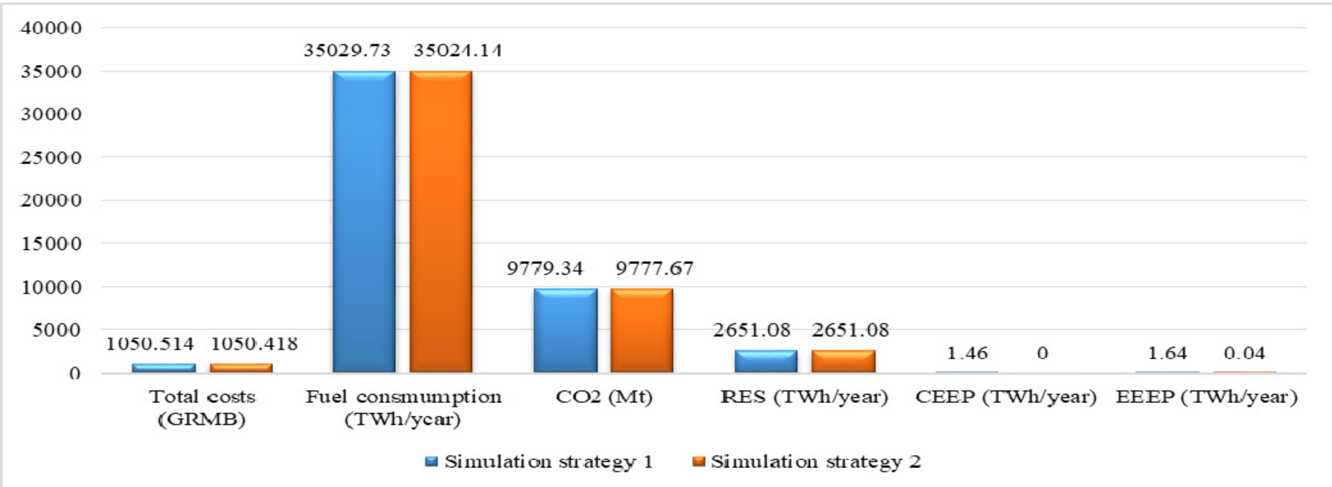

FIGURE 8. Summary performance of adding TS (Scenario 4).

to explicitly observe its effect on system parameters. Coal is cheaper than Ngas and replacement of all coal boilers with HP leads to lower fuel consumption and emissions. Heat pump performance is assessed by the Coefficient of Performance (COP) which is determined by the ratio of heat output to electricity input. COP varies with temperature fluctuations but by virtue of simplicity, this research considered its value to be constant. Higher HP COP in comparison to a boiler efficiency makes it more efficient and produces less emission per kWh. Hence, HP is preferred over boiler in terms of higher efficiency as it lowers carbon footprints from 9852 to 9822 Mt. Nonetheless, the high initial costs of HP accrue the total costs in comparison to scenario 2 (from 1053 to 1054 GRMB) as explicated in Figure 7.

E. SCENARIO 4 – THERMAL STORAGE ADDITION

Thermal storage stores surplus energy and detaches that energy when needed. It is considered the most feasible option for load reduction, energy savings and emission reductions [54]. In this work, TS addition is carried out according to the golden rule that says it should be around 5 hours of average heat demand. This storage capacity in the model is used to minimize power producing components generation with electricity export. TS integration along with boilers and CHP in the district heating system improves potential flexibility. It is charged when electricity production is shifted from TPP to CHP plants. TS discharging reduces CHP and boilers consumptions that result in more cost-saving than scenario 3 (from 1054 to 1050 GRMB) and alleviate Mt CO_2 as well (from 9822 to 9779 Mt) which is demonstrated in Figure 8.

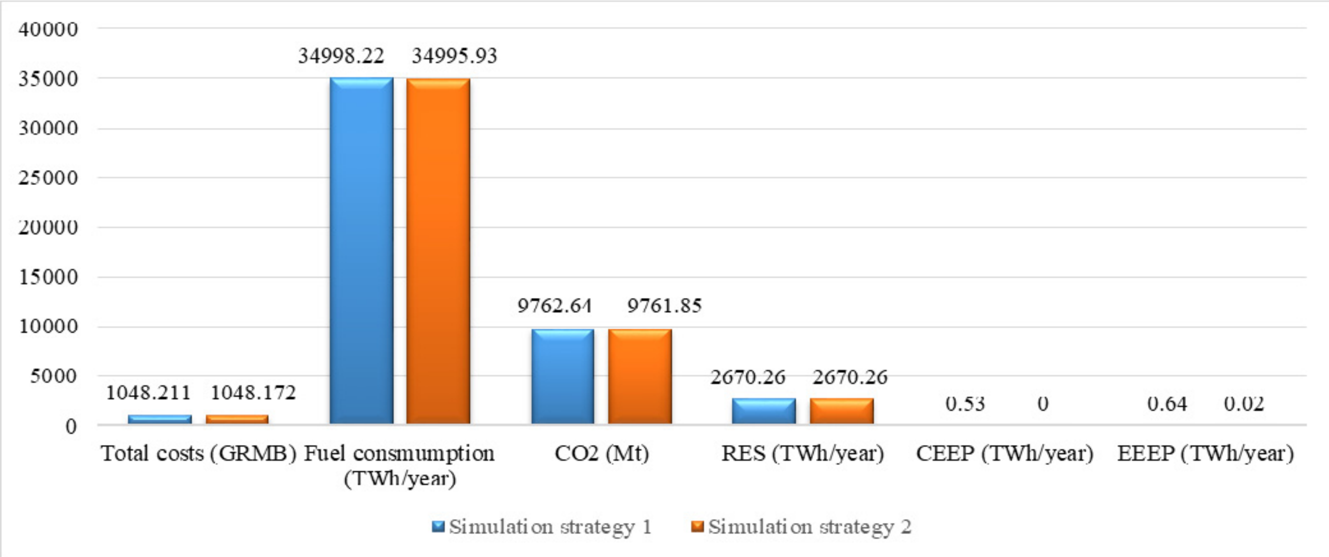

FIGURE 9. **Summary performance of adding DR (Scenario 5).**

TABLE 7. **Evaluation of all scenarios.**

Objective functions	Simulation strategy 1 Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Simulation strategy 2 Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Total costs (GRMB)	1062.546	1053.433	1054.131	1050.514	1048.211	1062.546	1053.31	1054.035	1050.418	1048.172
Fuel consumption (TWh/year)	36540.72	35285.65	35164.15	35024.14	34998.22	36540.72	35278.47	35158.56	35024.14	34995.93
CO2 emission (Mt)	10542.89	9852.42	9822.22	9779.34	9762.64	10542.89	9849.94	9820.3	9777.67	9761.85
RES (TWh/year)	1810.42	2651.08	2651.08	2651.08	2670.26	1810.42	2651.08	2651.08	2651.08	2670.26

F. SCENARIO 5 – DEMAND RESPONSE ADDITION

Demand response helps to address the challenges associated by integrating VRES because of their volatile nature that improves system stability and also reduces capital costs [55], [56]. In this work, demand response is introduced in the form of load shifting and is assumed to be 10% of the total electricity demand. DR implementation requires instruments like smart meters and advance metering infrastructure. Therefore, in order to cover its effect on system parameters, the costs of such devices are inserted in 'additional cost tab section' of EnergyPLAN.

Demand response acts like an additional storage and deemed a promising measure to integrate more VRES that intensely reduces CO_2 emission from 9779 to 9762 Mt and fuel consumption from 35029 to 34998 TWh/year in comparison to scenario 4. This not only reduces dependency on fossil fuel sources but also makes the system economically viable. Figure 9 inferred that annual costs (from 1050 to 1048 GRMB) are also reduced in comparison to the rest of the scenarios.

Reduction in all the objective functions in this scenario suggests valuable insight on the role of DR in IES.

All scenarios quantitative comparison is summarized in Table 7 which depicts that an integrated energy system helps to make system decarbonized, efficient and cost-effective. Starting from scenario 1 to 5, VRES share has been increased to 32% while Mt CO_2 emissions and fuel consumptions decreased to 7.4% and 4.2% respectively that clearly indicates integrated energy role in decarbonizing the atmosphere. Moreover, other than making the atmosphere cleaner by facilitating VRES integration with the help of storage and demand response technologies, this work also proves to be cost effective as it saves more than 14 Billion Renminbi (GRMB). Results reveal that most significant energy savings are observed in scenario 5 which are shown in table 7.

V. CONCLUSION

This paper presents integrated energy system modeling that results in improving overall efficiency, reliability and flexibility. Energy system analysis tool EnergyPLAN is used to investigate different IES modeling scenarios of China for the year 2020 based on hourly distribution. The proposed work find the optimal combination of electricity, district and individual heating producing components in SEH by performing technical analysis with two simulation strategies for five different scenarios. The results indicate that no energy is imported to fulfill electricity and heat demands while simulation strategy 2 produces exportable surplus electricity that can be sold if needed. In comparison to scenario 1, wind and solar penetration is increased in scenario 2 by 220 and 150 GW that leads to reduce the cost, fuel consumption and emissions to 9 GRMB, 1255 TWh/year and 690 Mt respectively. In scenario 3, fuel consumption and Mt CO_2 emissions are reduced because Ngas boilers are replaced with efficient heat pumps. Thermal storage addition in scenario 4 decreases CHP production that results in minimizing all objective functions than scenarios 1-3. Finally, demand response addition facilitates maximum amount of VRES integration that makes scenario 5 best among the rest of scenarios in terms of increasing the share of RES up to 2670 TWh/year and minimizing objective functions by 14 GRMB, 1542 TWh/year and 780 Mt.

This work can be extended to model MEC that also incorporate cooling and hydrogen demands in SEH to perform technical as well as market economic optimization. This may add a slight complexity to the system but plays a vital role in decreasing operation costs and enhancing system flexibility. Reduction in costs and increasing percentage of renewable energy sources in the near future will encourage heat pump penetration beyond domestic sector to develop a low carbon society.

NOMENCLATURE

A. INDICES

t	Time period of one whole year = 7874 hours
x	Type of energy $x = e(electricity)\ or\ h(heat)$
e	Represents electricity
h	Represent heat
$C.F$	Correction factor that adjusts differences between production and capacity
f	Total amount of fuel
d	Energy production distribution between 8784 values

B. CONSTANTS

η_e^T	Transformer efficiency
η_e^s	PV efficiency
η_e^w	Wind turbine generator efficiency
η_e^{hydro}	Hydropower plant efficiency
η_e^{geo}	Geothermal power plant efficiency
η_e^{NPP}	NPP efficiency
η_e^C, η_h^C	CHP electric and thermal efficiency
η_h^B	Boiler efficiency
$\eta_{x,ch}$, $\eta_{x,dis}$	Charging and discharging efficiency
COP^{hp}	Coefficient of performance of HP
δ_{xs}	Storage loss of energy storage device
P_e^d	Electricity demand for year 2020
P_{dh}^d, P_{ih}^d	DH and IH demand for year 2020
v	Dispatch factor

C. VARIABLES

P_e^{tot}	Total power generated
P_{in}^f	Total fuel input
P_{in}^{RES}, P_{in}^C, P_{in}^{NPP}, P_{in}^{TPP}	Total power supplied to RES, CHP, NPP and TPP respectively.
$P_{e,in}^{hp}$	Total electricity input to HP
P_{in}^B	Total input supply to boiler
P_{tot}^B	Total heat generated by boilers
$P_{\max}^B$	Maximum heat that can be generated by boilers.
P_{dh}^B, P_{ih}^B	boilers heat supplied to DH and IH
P_e^{out}, P_h^{out}	Electricity and heat output
P_{in}^w	Total wind input supply to wind turbine
P_{in}^s	Total solar irradiances to PV
P_{in}^{geo}	Total input supply to geothermal plant.
P_e^{RES}, P_e^{NPP}, P_e^{PP2}, P_e^C	Electricity generated by RES, NPP, TPP and CHP respectively
P_h^C, P_h^B, P_h^{hp}	Heat generated by CHP, boiler and heat pump respectively.
P_e^{SHDO}, P_e^{SHUP}	Total shift down and shift up power
P_{dh}^{out}, P_{ih}^{out}	DH and IH output
C^w, C^s	Wind and solar capacity factor
W^{hydro}	Annual water supply
S_{xs}^t	Stored energy before charging
S_x^{ch}, S_x^{dis}	Storage charged discharged capacity
$P_{x,ch}^{total}$, $P_{x,dis}^{total}$	Charging and discharging power
$P_{x,ch}^{\max}$, $P_{x,dis}^{\max}$	Maximum charging and discharging power
E	Demand price elasticity
∂P^d	Change in demand
$P_{x,o}^d$	Initial demand without DR
$\partial\lambda$, λ	Change in price and day/hour ahead price
$P_x^{d(\min)}$, $P_x^{d(\max)}$	Minimum and electricity demand of heat or electricity
μ	Binary variable
R^C	CHP Electrical ramping rate
En_x	Electric or thermal energy stored capacity

REFERENCES

[1] G. Bridge, B. Özkaynak, and E. Turhan, "Energy infrastructure and the fate of the nation: Introduction to special issue," *Energy Res. Social Sci.*, vol. 41, pp. 1–11, Jul. 2018.
[2] R. W. McCarthy and J. M. Ogden, and D. Sperling, "Assessing reliability in energy supply systems," *Energy Policy*, vol. 35, no. 4, pp. 2151–2162, 2007.
[3] E. Widl *et al.*, "Studying the potential of multi-carrier energy distribution grids: A holistic approach," *Energy*, vol. 153, pp. 519–529, Jun. 2018.
[4] T. Krause, G. Andersson, K, Frohlich, and A. Vaccaro, "Multiple-energy carriers: Modeling of production, delivery, and consumption, *Proc. IEEE*, vol. 99, no. 1, pp. 15–27, Jan. 2011.

[5] Y. Wang, H. Yu, M. Yong, Y. Huang, F. Zhang, and X. Wang, "Optimal scheduling of integrated energy systems with combined heat and power generation, photovoltaic and energy storage considering battery lifetime loss," *Energies*, vol. 11, no. 7, p. 1676, 2018.
[6] B. Kroposki, "Integrating high levels of variable renewable energy into electric power systems," *J. Modern Power Syst. Clean Energy*, vol. 5, no. 6, pp. 831–837, 2017.
[7] A. Rodrigues and D. T. M. Dentinho, "Electrical energy storage systems feasibility; The case of Terceira Island," *Sustainability*, vol. 9, no. 7, p. 1276, 2017.
[8] J. Y. Mo and W. Jeon, "How does energy storage increase the efficiency of an electricity market with integrated wind and solar power generation—A case study of Korea," *Sustainability*, vol. 9, no. 10, p. 1797, 2017.
[9] Y. Shan *et al.*, "Methodology and applications of city level CO_2 emission accounts in China," *J. Cleaner Prod.*, vol. 161, pp. 1215–1225, Sep. 2017.
[10] M. F. Tahir, C. Haoyong, I. I. Idris, N. A. Larik, and S. U. Adnan, "Demand response programs significance, challenges and worldwide scope in maintaining power system stability," *Int. J. Adv. Comput. Sci. Appl.*, vol. 9, no. 6, pp. 121–131, 2018.
[11] W. Xiong, Y. Wang, B. Vad Mathiesen, H. Lund, and X. Zhanga, "Heat roadmap China: New heat strategy to reduce energy consumption towards 2030," *Energy*, vol. 81, pp. 274–285, Mar. 2015.
[12] S. Werner, "International review of district heating and cooling," *Energy*, vol. 137, pp. 617–631, Oct. 2017.
[13] J. Zhang and L. D. Lucia, "A transition perspective on alternatives to coal in Chinese district heating," *Int. J. Sustain. Energy Planning Manage.*, vol. 6, pp. 49–69, Sep. 2015.
[14] W. Su, "Letter including autonomous domestic mitigation actions," Dept. Climate Change, Nat. Develop. Reform Commission China, Beijing China, 2009.
[15] F. Dong, Y. Hua, and B. Yu, "Peak carbon emissions in China: Status, key factors and countermeasures–A literature review," *Sustainability*, vol. 10, no. 8, p. 2895, 2018.
[16] J. Zhu and Z. Zhao, "Chinese electric power development coordination analysis on resource, production and consumption: A provincial case study," *Sustainability*, vol. 9, no. 2, p. 209, 2017.
[17] K. J. Chua, S. K. Chou, and W. M. Yang, "Advances in heat pump systems: A review," *Appl. Energy*, vol. 87, no. 12, pp. 3611–3624, 2010.
[18] M. Geidl, G. Koeppel, P. Favre-Perrod, B. Klockl, G. Andersson, and K. Frohlich, "Energy hubs for the future," *IEEE Power Energy Mag.*, vol. 5, no. 1, pp. 24–30, Jan./Feb. 2007.
[19] M. Mohammadi, Y. Noorollahi, B. Mohammadi-Ivatloo, and H. Yousefi, "Energy hub: From a model to a concept–a review," *Renew. Sustain. Energy Rev.*, vol. 80, pp. 1512–1527, Dec. 2017.
[20] S. Klyapovskiy, S. You, H. W. Bindner, and H. Cai, "Optimal placement of a heat pump in an integrated power and heat energy system," in *Proc. 9th Annu. IEEE Green Technol. Conf. (GreenTech)*. Mar. 2017, pp. 246–253.
[21] Y. Song, W. Hu, Z. Zhang, R. Hu, Q. Huang, and Z. Chen, "Optimal operation and location of heat pumps in the integrated energy systems," in *Proc. IEEE Conf. Energy Internet Energy Syst. Integration (EI2)*. Nov. 2017, pp. 1–6.
[22] E. M. Wanjiru, S. M. Sichilalu, and X. Xia, "Optimal operation of integrated heat pump-instant water heaters with renewable energy," *Energy Procedia*, vol. 105, pp. 2151–2156, May 2017.
[23] A. D. Smith, P. J. Mago, and N. Fumo, "Benefits of thermal energy storage option combined with CHP system for different commercial building types," *Sustain. Energy Technol. Assessments*, vol. 1, pp. 3–12, Mar. 2013.
[24] G. Li and X. Zheng, "Thermal energy storage system integration forms for a sustainable future," *Renew. Sustain. Energy Rev.*, vol. 62, pp. 736–757, Sep. 2016.
[25] K. T. Ponds, A. Arefi, A. Sayigh, and G. Ledwich, "Aggregator of demand response for renewable integration and customer engagement: Strengths, weaknesses, opportunities, and threats," *Energies*, vol. 11, no. 9, p. 2391, 2018.
[26] A. Pfeifer, V. Dobravec, L. Pavlinek, G. Krajačić, and N. Duić, "Integration of renewable energy and demand response technologies in interconnected energy systems," *Energy*, vol. 161, pp. 447–455, Oct. 2018.
[27] R. Wu, Z. Pan, and L. Tang, "Smart dispatch system for integrated energy systems with demand response," in *Proc. IEEE Conf. Energy Internet Energy Syst. Integr. (EI2)*, Nov. 2017, pp. 1–6.
[28] L. Liu, T. Zhu, Y. Pan, and H. Wang, "Multiple energy complementation based on distributed energy systems–Case study of Chongming county, China," *Appl. Energy*, vol. 192, pp. 329–336, Apr. 2017.
[29] G. Zhao, J. M. Guerrero, K. Jiang, and S. Chen, "Energy modelling towards low carbon development of Beijing in 2030," *Energy*, vol. 121, pp. 107–113, Feb. 2017.
[30] L. Hong, H. Lund, and B. Möller, "The importance of flexible power plant operation for Jiangsu's wind integration," *Energy*, vol. 41, no. 1, pp. 499–507, 2012.
[31] H. Lund, "EnergyPLAN, advanced energy systems analysis computer model," Sustain. Energy Planning Res. Group, Aalborg Univ., Aalborg, Denmark, Documentation Version, 2017.
[32] H. A. Aalami, M. P. Moghaddam, and G. R. Yousefi, "Demand response modeling considering interruptible/curtailable loads and capacity market programs," *Appl. Energy*, vol. 87, no. 1, pp. 243–250, 2010.
[33] H. Lund, "EnergyPLAN: Advanced energy system analysis computer model," Users Manual Documentation Version 13, Aalborg Univ., Aalborg, Denmark, 2017.
[34] H. Lund and A. N. Andersen, "Optimal designs of small CHP plants in a market with fluctuating electricity prices," *Energy Convers. Manage.*, vol. 46, no. 6, pp. 893–904, 2005.
[35] H. Lund, G. Šiupšinskas, and V. Martinaitis, "Implementation strategy for small CHP-plants in a competitive market: The case of Lithuania," *Appl. Energy*, vol. 82, no. 3, pp. 214–227, 2005.
[36] J. J. Vidal-Amaro, P. A. Østergaard, and C. Sheinbaum-Pardo, "Optimal energy mix for transitioning from fossil fuels to renewable energy sources–the case of the Mexican electricity system," *Appl. Energy*, vol. 150, pp. 80–96, Jul. 2015.
[37] A. Pina, C. A. Silva, and P. Ferrão, "High-resolution modeling framework for planning electricity systems with high penetration of renewables," *Appl. Energy*, vol. 112, pp. 215–223, Dec. 2013.
[38] P. A. Østergaard, "Reviewing optimisation criteria for energy systems analyses of renewable energy integration," *Energy*, vol. 34, no. 9, pp. 1236–1245, 2009.
[39] D. Connolly, H. Lund, B. V. Mathiesen, and M. Leahy, "The first step towards a 100% renewable energy-system for Ireland," *Appl. Energy*, vol. 88, no. 2, pp. 502–507, 2011.
[40] B. Ćosić, G. Krajačić, N. Duić, "A 100% renewable energy system in the year 2050: The case of Macedonia," *Energy*, vol. 48, no. 1, pp. 80–87, 2012.
[41] H. Lund and B. V. Mathiesen, "Energy system analysis of 100% renewable energy systems–The case of Denmark in years 2030 and 2050," *Energy*, vol. 34, no. 5, pp. 524–531, 2009.
[42] D. Connolly and B. V. Mathiesen, "A technical and economic analysis of one potential pathway to a 100% renewable energy system," *Int. J. Sustain. Energy Planning Manage.*, vol. 1, pp. 7–28, May 2014.
[43] Z. B. Medić, B. Cosic, and N. Duic, "Sustainability of remote communities: 100% renewable Island of Hvar," *J. Renew. Sustain. Energy*, vol. 5, no. 4, 2013, Art. no. 041806.
[44] H. Lund, N. Duić, G. Krajačić, and M. da Graça Carvalho "Two energy system analysis models: A comparison of methodologies and results," *Energy*, vol. 32, no. 6, pp. 948–954, 2007.
[45] B. Petroleum, *BP Energy Outlook 2016 Edition*. London, U.K.: BP Press, 2016.
[46] L. Suganthi and A. A. Samuel, "Energy models for demand forecasting—A review," *Renew. Sustain. energy Rev.*, vol. 16, no. 2, pp. 1223–1240, 2012.
[47] I. Energy and C. Change, "World energy outlook special report (2015)," Org. Econ. Cooperat. Develop./Int. Energy Agency, Paris, France, 2017, p. 37.
[48] (2017). *Water Regimen Information*. Yichang, China, China Three Gorges Corporation. [Online]. Available: http://www.ctgpc.com.cn/
[49] (2017). *State Grid Corporation Power Supply and Sale Statistic*. Beijing, China, State Grid Corporation. [Online]. Available: http://www.sgcc.com.cn/
[50] *Annual Report of China's Power Sector Development 2017*, China Electr. Press, Beijing, China, 2017.
[51] *China Power Industry Statistic in 2017*, China Electr. Council, Beijing, China, 2017.
[52] K.-I. Nishio and Y. Hoshino, "Impacts of electrification on CO_2 emission reduction potentials in the G7 Countries," 3rd ed., China Power Ind. Statist., China Electr. Council, Beijing, China, 2007.
[53] A. D. Carvalho, D. Mendrinos, and A. T. De Almeida, "Ground source heat pump carbon emissions and primary energy reduction potential for heating in buildings in Europe–results of a case study in Portugal," *Renew. Sustain. Energy Rev.*, vol. 45, pp. 755–768, May 2015.

[54] P. Arce, M. Medrano, A. Gil, E. Oró, and L. F. Cabeza, "Overview of thermal energy storage (TES) potential energy savings and climate change mitigation in Spain and Europe," *Appl. Energy*, vol. 88, no. 8, pp. 2764–2774, 2011.
[55] P. Siano, "Demand response and smart grids—A survey," *Renew. Sustain. Energy Rev.*, vol. 30, pp. 461–478, Feb. 2014.
[56] M. C. Vlot, J. D. Knigge, and J. G. Slootweg, "Economical regulation power through load shifting with smart energy appliances," *IEEE Trans. Smart Grid*, vol. 4, no. 3, pp. 1705–1712, Sep. 2013.

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