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Full-length article

Economic analysis of energy interconnection between Europe and China with 100% renewable energy generation

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Abstract: The economic benefits of interconnecting the power grids of Europe (EU) and China (CN) were assessed considering 100% reliance on renewable energy (RE). Four different scenarios, energy storage without interconnection, installing additional renewable energy sources without interconnection, energy storage with interconnection, and installing additional RE sources with interconnection, were considered for the economic benefit analysis. A comparative study of these four scenarios was conducted to identify the best option for achieving hourly power balance. Further, sensitivity analysis was carried out to demonstrate the robustness of the results. Electricity interconnection between CN and EU decreases the annual additional costs by more than 30% when compared to the absence of interconnection, which demonstrates the necessity and benefits of CN-EU electricity interconnection.

Keywords: Global Energy Interconnection, Ultra High Voltage Direct Current (UHVDC), High Voltage Direct Current (HVDC), Energy storage, Economic analysis, Energy reserve, Grid construction.

1 Introduction

Climate change, resource scarcity, environmental pollution, and unbalanced development all pose a major challenge to the sustainable development of society. The fundamental solution is to promote global energy transformation, wherein RE and energy efficiency are the main pillars [1-3]. Increasing energy connectivity is key to implement the energy transformation [1-8]. There are several concepts relevant to energy connectivity, e.g., global energy interconnection (GEI) [3-5], which refers to "Ultra-High Voltage Grid + Smart Grid + RE", energy internet (EI) [6], which focuses on the interactions between consumers, distributed generation, and smart distribution networks, and global power & energy internet (GPEI) [7, 8], which highlights the interconnection of electricity, heat, and gas networks as well as transport networks at four layers, i.e. transnational, national, city and consumer layers.

CN and Europe EU are two of the most important energy-consuming centers of the world and have different available RE sources. Electricity interconnection of the two areas could cover regions in up to eight time zones. As RE generation and demand patterns are different in different time zones, this will facilitate utilization of different renewables. Further, with the breakthrough development of UHVDC links [9, 10], which offer advantages of a large power transfer capacity over long distances with low power loss, the CN-EU electricity link has become technically feasible. Moreover, CN's goal to export industrial

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overcapacity under its “the Belt and Road” initiative coincides with EU’s goals of reducing carbon footprint and decreasing nuclear energy [11]. Therefore, energy interconnection would be beneficial to both parties and can potentially receive policy support of both CN and EU governments. In general, as a key part of GEI, electricity interconnection between CN and EU is increasingly gaining momentum.

Studies providing insights on the planning of energy interconnection between CN and EU under a high RE penetration scenario are limited. Based on the basic concept of GEI and the roadmap for its implementation [1, 3], the GEI backbone grid was launched at the Global Energy Interconnection Conference held in 2018. During this conference, two transmission corridors were proposed to achieve CN-EU energy interconnection and their development orientation and key UHVDC projects were discussed [11, 12]. In-depth research conducted by EU’s Joint Research Centre (JRC) explored three potential routes for CN-EU electricity linkage to achieve maximum RE utilization while avoiding harsh terrain [13]. Researchers [14, 15] proposed meeting the electricity demand of all sectors in America and other 139 countries with 100% clean and renewable wind, water, and sunlight. They estimated the annual average power demand for each country and proposed promising portfolios of RE generation based on the annual energy balance of each country. However, energy interconnection among different countries was not taken into account. In all the above studies, hourly power balance was not given enough attention, which is necessary for practically matching power supply and demand due to the seasonal, weekly and daily characteristics of RE generation.

Therefore, the aim of this study is to investigate whether the CN-EU electricity interconnection has economic benefits and, if so, determine the optimal capacity of the UHVDC links considering the hourly power balance during typical weeks in 2050, when the electricity systems of both CN and EU are expected to rely only on RE. In Section 2, a method for obtaining hourly power generation and supply data for CN and EU in 2050 according to the European electricity statistics of 2017 and the annual RE electricity and demand in both areas is introduced [15]. Mixed integer linear programming (MILP) optimization models for determining the optimal additional RE, energy storage, and interconnection line capacities on the basis of the existing capacity deployed according to the annual energy balance are described in Section 3. Case studies of energy interconnection are presented in Section 4. In this study, two alternative measures to achieve hourly power balance and scenarios with and without CN-EU interconnection are compared and analyzed. Further, the sensitivity of the annual cost and installed transmission line capacity to varying per unit cost of different facilities is assessed. Finally, the conclusions drawn from the study are presented in Section 5.

2 Data for system analysis

This study focuses on the electricity demand of CN and EU assumed to be met only with RE by 2050, as opposed to other end-use fuel demands (e.g., heat, oil, natural gas, and coal) [15]. The annual demand and installed capacity of RE and the corresponding actual power delivered to end users can be obtained from [15]. The annual demand and generation are expressed in terms of the average power, which is equal to the annual energy divided by the total annual hours.

To model the electricity system more realistically and estimate the annual cost more accurately, the hourly power balance during typical weeks, one for each season, was considered. However, data pertaining to the hourly demand and hourly available solar, wind, and hydro power in 2050 for both CN and EU do not exist and therefore need to be generated. The proposed procedure for obtaining the relevant data for EU based on the European electricity statistics of 2017 from the European network of transmission system operators (ENTSO-E) [16] and annual energy estimates for 2050 [15] is described below.

- Based on the seasonal demand and solar and wind power generation data for EU in 2017, the capacity factors (CFs) of different RE sources during each season were calculated.
- These CFs were scaled to match the annual CFs of each type of RE in 2050. Thereafter, the average power generation and demand during each season was obtained using

$$P^{\mathrm{avg}}_{\mathrm{i,j,z}} = CF_{\mathrm{i,j,z}} Cap_{\mathrm{i,z}} \tag{1}$$

where $P^{\mathrm{avg}}_{\mathrm{i,j,z}}$(GW) represents the average power from RE source *i* during season *j* in area *z* (i.e., CN or EU). $CF_{\mathrm{i,j,z}}$ is the CF of RE source *i* during season *j*, and $Cap_{\mathrm{i,z}}$ denotes the installed capacity of RE *i* in area *z* in 2050.

- Based on the normalized curve of hourly generation and demand in 2017 and available average power, the actual values can be calculated using

$$P^{\mathrm{avi}}_{\mathrm{t,i,j,z}} = (P^{\mathrm{avg}}_{\mathrm{i,j,z}} / ratio_{\mathrm{i,j,z}}) \cdot c_{\mathrm{t,i,j,z}} \tag{2}$$

where $P^{\mathrm{avi}}_{\mathrm{t,i,j,z}}$(GW) represents hourly available power from RE source *i* during season *j* at time *t*. $ratio_{\mathrm{i,j,z}}$ denotes the ratio between the maximum power and average power from RE source *i*, and $c_{\mathrm{t,i,j,z}} \in [0,1]$ is the coefficient representing

RE generation at time *t,* accounting for maximum power.

The procedure for obtaining the hourly power data for CN in 2050 is similar to that for EU. However, as hourly electricity data for CN are limited, the profiles of demand and RE generation are assumed to be similar to those for EU.

The seasonal average solar, wind, and hydro power and demand for CN and EU in 2050 are given in Table 1 and Table 2, respectively.

Table 1 Seasonal average power from different RE sources and load for CN in 2050 (GW)

Season	Wind	Solar	Hydro	Load	Total	Total-Load Diff.
Spring	384	378	29	887	791	-96
Summer	285	835	39	911	1,160	249
Autumn	254	769	52	1,040	1,075	35
Winter	441	298	40	966	779	-187

Note: “1”-spring (January-March), “2”-summer (April-June), “3”-autumn (July-September), and “4”-winter (October -December).

Table 2 Seasonal average power from different RE sources and load for EU in 2050 (GW)

Season	Wind	Solar	Hydro	Load	Total	Total-Load Diff.
Spring	241	152	32	526	427	-99
Summer	179	335	35	441	547	106
Autumn	159	309	32	441	499	62
Winter	277	120	30	499	429	-70

Hydro energy accounts for only a small share of the total power generated. This is because the installed capacity of hydropower in 2050 is assumed to be the same as that in 2015 [15].

The installed RE capacity is deployed on the basis of annual energy balance, and therefore seasonal energy cannot be guaranteed (Table 1 and Table 2) owing to the seasonal characteristics of RE generation, which depends largely on the availability of natural resources. In this study, two alternative measures to achieve hourly power balance (energy storage and additional RE capacity) in CN and EU are proposed.

3 Problem formulation

The aim of this study is to determine whether electricity interconnection between CN and EU will be beneficial and, if so, estimate the optimal capacity of transmission lines. In addition to the installed capacity proposed according to the annual energy balance, additional energy storage and RE capacity should be installed to achieve hourly power balance. Hourly power balance during four typical weeks (one week of each season i.e., 168 hours per season) was selected to represent the average hourly power balance for the entire year. Finally, MILP-based investment optimization models that consider the options of UHVDC transmission interconnectors, energy storage, and additional RE capacity were constructed.

3.1 Modeling of RE generation, electrical storage, and transmission line

3.1.1 Wind, solar, and hydro power generation

For 100% RE systems, it is essential to dispatch the output power of the power generation facilities. For simplicity, as hydro power is less fluctuating and intermittent than solar or wind power, it is assumed to be constant during each typical week. A simple inequality is employed as follows:

$$p^{\mathrm{RE}}_{\mathrm{t,i,j,z}} \leqslant P^{\mathrm{avi}}_{\mathrm{t,i,j,z}} \tag{3}$$

where $p^{\mathrm{RE}}_{\mathrm{t,i,j,z}}$ and $P^{\mathrm{avi}}_{\mathrm{t,i,j,z}}$ (GW) represent the actual and available power from RE source *i* during season *j* at time *t* in area *z* (i.e., CN or EU).

3.1.2 Energy storage

Hourly power balance can be achieved through energy storage. The energy stored in periods with redundant power generation can then be supplied as required, which alleviates the mismatch of power supply and demand. The storage is modeled as

$$\begin{cases} E_{\mathrm{t,j,z}} = (1-\tau)E_{\mathrm{t-1,j,z}} + (p^{\mathrm{ch}}_{\mathrm{t,j,z}}\eta_{\mathrm{ch}} - p^{\mathrm{dis}}_{\mathrm{t,j,z}}/\eta_{\mathrm{dis}})\Delta t \\ E_{\mathrm{0,j,z}} = E_{\mathrm{T,j,z}} \\ \gamma^{\min}\psi^{\mathrm{st}}_{\mathrm{z}} \leqslant E_{\mathrm{t,j,z}} \leqslant \gamma^{\max}\psi^{\mathrm{st}}_{\mathrm{z}} \end{cases} \tag{4}$$

where $p^{\mathrm{ch}}_{\mathrm{t,j,z}}$ and $p^{\mathrm{dis}}_{\mathrm{t,j,z}}$(GW) are respectively the charging and discharging powers of the energy storage unit in area *z* during season *j* at time *t*. η_{ch} and η_{dis} denote the charging and discharging efficiency, and Δt [1 h in this study] is the time interval. $E_{\mathrm{t,j,z}}$, $E_{\mathrm{t-1,j,z}}$, $E_{\mathrm{0,j,z}}$, and $E_{\mathrm{T,j,z}}$ (GWh) represent the energy stored at times *t*, *t*-1, 0, and *T* (*T* is 168 h in this study), respectively, in area *z*. $\psi^{\mathrm{st}}_{\mathrm{z}}$ (GWh) denotes the installed capacity, and $\gamma^{\min}$ and $\gamma^{\max}$ (0.1 and 0.9, respectively, in this study) are the minimum depth of discharge (DoD) and maximum DoD, respectively.

3.1.3 Transmission line

For the long-distance and high power exchange between CN and EU, the ±1100 kV UHVDC line is employed whose transmission capacity and distance are 12 GW per line and 5000 km, respectively [3]. By combining several lines, an equivalent line *l* is obtained and modeled as follows:

$$p^{\mathrm{end}}_{\mathrm{t,l,j,z,n}} = p^{\mathrm{start}}_{\mathrm{t,l,j,z,n}}(1-\delta L_{\mathrm{z,n}}) \tag{5}$$

where $p^{\mathrm{start}}_{\mathrm{t,l,j,z,n}}$ and $p^{\mathrm{end}}_{\mathrm{t,l,j,z,n}}$ (GW) are the powers at the starting and ending points of line *l* at time *t* in season *j* with the transfer occurring from area *z* to area *n*. δ denotes the power loss (%/1000 km) and $L_{\mathrm{z,n}}$ (km) is the distance.

3.2 Objective function

As mentioned above, two alternative measures are proposed to address the power deficit for balancing supply and demand in each hour. “Measure 1” is to install electrical energy storage devices, and “Measure 2” is to install devices for additional renewable energy generation. Utilizing different measures, two optimization models based on MILP were constructed whose objective is minimizing the annual additional investment in the newly installed facilities and transmission lines. It is noted that a small amount of additional RE should be installed to cover the charging/discharging power loss and seasonal power deficits when “Measure 1” is employed. The objective function for “Measure 1” is expressed mathematically as follows:

$$\begin{aligned} F = &\sum_{i,z} CFR^{\mathrm{RE}}_{\mathrm{i}}(\psi^{\mathrm{RE}}_{\mathrm{i,z}}\omega^{\mathrm{RE}}_{\mathrm{i,z}}) + CFR^{\mathrm{st}}\sum_{z}\psi^{\mathrm{st}}_{\mathrm{z}}\omega^{\mathrm{st}}_{\mathrm{z}} \\ &+ CFR^{\mathrm{line}}\sum_{l}(\psi^{\mathrm{line}}_{\mathrm{l,z,n}}\omega^{\mathrm{line}}_{\mathrm{l,z,n}}y_{\mathrm{l,z,n}}) \end{aligned} \tag{6}$$

where $CFR^{\mathrm{RE}}_{\mathrm{i}}$, CFR^{l}, and CFR^{st} are the capital recovery factors (CFRs) of different RE capacities, transmission lines, and energy storages, calculated using equation (7). $\psi^{\mathrm{RE}}_{\mathrm{i,z}}$ (GW) and $\psi^{\mathrm{st}}_{\mathrm{z}}$ (GWh) denote the installed capacity of different facilities in area *z*. $\omega^{\mathrm{RE}}_{\mathrm{i,z}}$ (million/GW) and $\omega^{\mathrm{st}}_{\mathrm{z}}$ (million /GWh) are the investment costs per unit of the different facilities. $\psi^{\mathrm{line}}_{\mathrm{l,z,n}}$ (GW) and $\omega^{\mathrm{line}}_{\mathrm{l,z,n}}$ (million/GW) denote the capacity and cost of line *l* connecting areas *z* and *n*. $y_{\mathrm{l,z,n}} \in \{0,1\}$ denotes whether line *l* is installed.

$$CFR = \frac{ir(1+ir)^{\mathrm{life}}}{(1+ir)^{\mathrm{life}}-1} \tag{7}$$

where *ir* (5% in this study) is the interest rate and *life* is the lifespan of the facility [17].

Regarding the objective function for “Measure 2”, it can be obtained by simply removing the energy storage cost from (6).

3.3 Constraints

The constraints mainly include the maximum potential of the installed capacity, hourly power balance, and maximum outputs of facilities.

(1) Potential of the installed capacity

$$\psi^{\mathrm{RE}}_{\mathrm{i,z}} \leqslant \overline{\psi}^{\mathrm{RE}}_{\mathrm{i,z}} \tag{8-a}$$

$$\psi^{\mathrm{st}}_{\mathrm{z}} \leqslant \overline{\psi}^{\mathrm{st}}_{\mathrm{z}} \tag{8-b}$$

where $\overline{\psi}^{\mathrm{RE}}_{\mathrm{i,z}}$(GW) is the maximum potential capacity calculated according to the availability of raw resources and technical potential of different RE capacities in CN and EU, respectively. $\overline{\psi}^{\mathrm{st}}_{\mathrm{z}}$ (GWh) is the maximum allowable installed capacity of energy storage in each area.

(2) Hourly power balance

$$\begin{aligned} L_{\mathrm{t,j,z}} = &\sum_{i} p^{\mathrm{RE}}_{\mathrm{t,i,j,z}} + (x^{\mathrm{dis}}_{\mathrm{t,j,z}}p^{\mathrm{dis}}_{\mathrm{t,j,z}} - x^{\mathrm{ch}}_{\mathrm{t,j,z}}p^{\mathrm{ch}}_{\mathrm{t,j,z}}) \\ &+ \sum_{l}(x_{\mathrm{t,l,j.n,z}}p^{\mathrm{end}}_{\mathrm{t,l,j,n,z}} - x_{\mathrm{t,l,j,z,n}}p^{\mathrm{start}}_{\mathrm{t,l,j,z,n}}) \end{aligned} \tag{9}$$

where $L_{\mathrm{t,j,z}}$ (GW) is the demand of area *z* in season *j* at time *t*. $x^{\mathrm{dis}}_{\mathrm{t,j,z}}, x^{\mathrm{ch}}_{\mathrm{t,j,z}} \in \{0,1\}$ are dispatch factors representing whether the storage in area *z* at time *t* in season *j* is charging or discharging. $x_{\mathrm{t,l,j,n,z}} \in \{0,1\}$ is the dispatch factor indicating whether the power is transferred from area *n* to area *z* via line *l* at time *t* in season *j*.

(3) Maximum outputs of facilities

$$0 \leqslant p^{\mathrm{start}}_{\mathrm{t,l,j,z,n}} \leqslant x_{\mathrm{t,l,j,z,n}}\psi^{\mathrm{line}}_{\mathrm{l,z,n}} \tag{10}$$

Equation (10) indicates that the power through line *l* should be smaller than its rated capacity.

$$0 \leqslant p^{\mathrm{ch}}_{\mathrm{t,j,z}} \leqslant x^{\mathrm{ch}}_{\mathrm{t,j,z}}r^{\mathrm{st}}\psi^{\mathrm{st}}_{\mathrm{z}} \tag{11-a}$$

$$0 \leqslant p^{\mathrm{dis}}_{\mathrm{t,j,z}} \leqslant x^{\mathrm{dis}}_{\mathrm{t,j,z}}r^{\mathrm{st}}\psi^{\mathrm{st}}_{\mathrm{z}} \tag{11-b}$$

where r^{st} [0.25 in this study] is the ratio reflecting the relationship between the maximum charging/discharging power and capacity of energy storage.

(4) Linear model

$$x_{\mathrm{t,l,j.n,z}} + x_{\mathrm{t,l,z,n}} \leqslant 1 \tag{12-a}$$

$$x^{\mathrm{dis}}_{\mathrm{t,j,z}} + x^{\mathrm{ch}}_{\mathrm{t,j,z}} \leqslant 1 \tag{12-b}$$

$$x_{\mathrm{t,l,j.n,z}} \leqslant y_{\mathrm{l,z,n}} \tag{13}$$

Equations (12-a and -b) show that an identical line is not allowed to transfer power from the opposite direction, and an identical energy storage cannot charge and discharge at the same time. Equation (13) means the line can only be dispatched after installed.

It is noted that two variables are multiplied in equations (11-a and -b), which cause nonlinearity of the formulation. Equation (11-a) can be linearized as follows [18] and equation (11-b) can be linearized in a similar way:

$$\begin{cases} 0 \leqslant p^{\mathrm{ch}}_{\mathrm{t,j,z}} \leqslant r^{\mathrm{st}}\psi^{\mathrm{st}}_{\mathrm{z}} \\ p^{\mathrm{ch}}_{\mathrm{t,j,z}} + (r^{\mathrm{st}}\overline{\psi}^{\mathrm{st}}_{\mathrm{z}})(1-x^{\mathrm{ch}}_{\mathrm{t,j,z}}) \geqslant 0 \\ -p^{\mathrm{ch}}_{\mathrm{t,j,z}} + (r^{\mathrm{st}}\overline{\psi}^{\mathrm{st}}_{\mathrm{z}})x^{\mathrm{ch}}_{\mathrm{t,j,z}} \geqslant 0 \end{cases} \tag{14}$$

4 Case study

4.1 Case design

As mentioned earlier, the economic advantages of electricity interconnection between CN and EU via ±1100-kV UHVDC lines will be discussed in this section. Four cases based on the two measures are presented as follows.

Case 1: With "Measure 1" and without interconnection. The energy storage is deployed in CN and EU to achieve hourly power balance with a small amount of additional RE capacity installed to cover charging/discharging losses and seasonal power deficits. The interconnection between CN and EU is not considered in this case.

Case 2: With "Measure 2" and without interconnection. Additional RE is deployed in CN and EU to achieve hourly power balance. The interconnection between CN and that EU is not considered as in *Case 1*.

Case 3: With "Measure 1" and with interconnection. The energy storage and transmission lines are employed to achieve hourly power balance in both areas.

Case 4: With "Measure 2" and with interconnection. Additional RE capacity and transmission lines are employed to achieve hourly power balance in both areas.

Apart from the four cases mentioned above, the existing deployment of RE in 2050 based on the annual energy balance in CN and EU is considered as *Case 0*.

4.2 Settings of key parameters

The parameters of the facilities [19-21] and ±1100 kV UHVDC line [12, 22, 23] are given in Table 3.

The investment cost and lifespan of facilities are assumed to be the same in both CN and EU. Moreover, the investment cost for wind generation considers both the onshore and offshore generations. The ratio between onshore and offshore wind generation for the additional RE investment is equal to the ratio between the potential of the installed capacity minus the installed capacity in 2050 for onshore generation and that for offshore generation. Lithium-ion batteries are employed as storage facilities owing to their high energy density and low maintenance costs.

Table 3 Parameters of facilities and ±1100 kV UHVDC line

Type	Distance [km]	Cost [10^4 ¥/kW]	Life [years]	Other
Wind	–	1.87 (CN) 2.22 (EU)	20	–
Solar	–	1.45	25	–
Hydro	–	1.58	40	–
Storage	–	3548 (¥/kWh)	15	0.95 (η_{ch}, η_{dis})
±1100 kV	5600	1224 (104 ¥/km)	40	12 GW/line 2 %/1000 km

Note: 1$ = 6.6 ¥.

The installed capacities of different RE facilities for *Case 0* are given in Table 4, which are obtained by utilizing the ratio of electricity accounting for the total end-use electrified fuel in [15].

Table 4 Basic installed capacity of RE in 2050

Area	Onshore (GW)	Offshore (GW)	Solar (GW)	Hydro (GW)
CN	583.75	310.02	2,940.59	87.57
EU	337.38	226.63	1,282.16	72.07

The maximum potential capacities of different RE installations in CN and EU are given in Table 5[24, 25]. For the sake of simplicity, the capacities of RE facilities are expressed as times relative to the basic values in *Case 0* as shown in Table 4 in the remaining sections.

Table 5 Maximum potential capacity of RE in 2050

Area	Onshore	Offshore	Solar	Hydro
CN	3.46	3.46	>100	3.46
EU	4.97	8.77	>100	2.74

4.3 Results and analysis

4.3.1 Planning results

The capacities of the additional RE, energy storage, and lines for *Case 1* and *Case 3* are given in Table 6; those for *Case 2* and *Case 4* are given in Table 7. The annual costs for each case are given in Table 8.

Table 6 Capacities of facilities and lines for Cases 1 and 3

Type	Case 1		Case 3	
	CN	EU	CN	EU
Solar	1.00	1.00	1.00	1.00
Onshore	1.24	1.14	1.24	1.14
Offshore	1.24	1.28	1.24	1.28
Hydro	3.46	2.74	3.46	2.74
Storage [TWh]	17.50	6.03	11.24	2.39
Line (GW)	–		252	

Table 7 Capacities of facilities and lines for Cases 2 and 4

Type	Case 2		Case 4	
	CN	EU	CN	EU
Solar	1.00	1.00	1.00	1.00
Onshore	4.92	2.73	1.74	3.89
Offshore	4.92	4.37	1.74	6.64
Hydro	3.46	2.74	3.46	2.74
Line (GW)	–		648	

As observed in Table 6 and Table 7, the capacities of solar energy generation in all the four cases are the same as that in the basic case, i.e., *Case 0*, because hourly power deficits usually happen during nights when photovoltaics do not generate power. Increasing the capacity of solar energy generation makes no contribution to the supply if no extra storage capacity is installed. The costs for installing extra storage are high as well, hence, additional wind and hydro generation facilities are installed rather than solar generation facility. Moreover, we found that hydro generation reach its full potential in all cases, i.e., 3.76 and 2.65 in CN and EU, respectively, because of its lower cost per kW and long lifespan. It should be noted that in Case 2, the capacity of wind generation in CN exceeds its potential value of 3.46, which means hourly power balance in CN cannot be guaranteed by increasing RE capacity only, and an essential measure such as energy storage or interconnection is required.

Table 8 Annual additional costs of the four cases (billion ¥)

Case	RE	Storage	Line	Total	Decrease
1	859.81	8,045.42	0.00	8,905.23	0.00%
2	7,985.06	0.00	0.00	7,985.06	-10.33%
3	859.81	4,660.62	83.92	5,604.35	-37.07%
4	5,346.17	0.00	215.78	5,561.95	-37.54%

Data presented in Table 8 suggest that the electricity interconnection between CN and EU decreases the annual costs significantly, approximately 37.07% for Measure 1 corresponding to *Case 1* and *Case 3*, and 30.35% for Measure 2 corresponding to *Case 2* and *Case 4*. This demonstrates the necessity of interconnection between CN and EU. In addition, Measure 2 performs better than Measure 1 in both situations with and without interconnection under the current cost per unit, leading to 10.33% and 0.76% less annual additional costs, respectively. Further, it is obvious that the cost for installing transmission lines accounts for a small share in the total annual additional cost, approximately 1.50% in *Case 3* (Measure 1) and 3.88% in *Case 4* (Measure 2).

4.3.2 Hourly power exchange between CN and EU

The hourly power exchange through the lines connecting CN and EU in autumn is illustrated in Fig. 1 for *Case 3*, and in Fig. 2 for *Case 4*. The positive values indicate that power is transferred from EU to CN. The horizontal values are expressed in terms of the time in CN.

As displayed in Fig. 2, for *Case 4* relying on RE to achieve power balance, EU sends power to CN from approximately 8:00 pm to 8:00 am every day because the solar generation facilities in CN do not generate power during night whereas EU has plenty of solar and wind power during the same period. From approximately 11:00 am to 13:00 pm, solar generation facilities generate power of a higher level in CN owing to the higher solar radiation during this period and the redundant power is transferred from CN to EU. In contrast, the power exchange in *Case 3* shows more fluctuations and intermittency with generally lower power exchange (shown in Fig. 1), because the local energy storage in each area can alleviate the power mismatch between the demand and supply locally by carrying the energy from day to night.

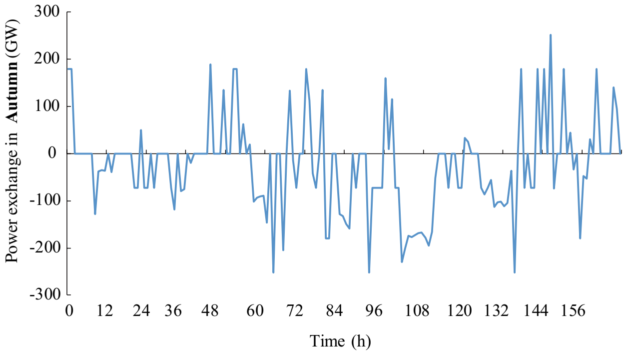

Fig. 1 Power exchange between CN and EU in Autumn for Case 3

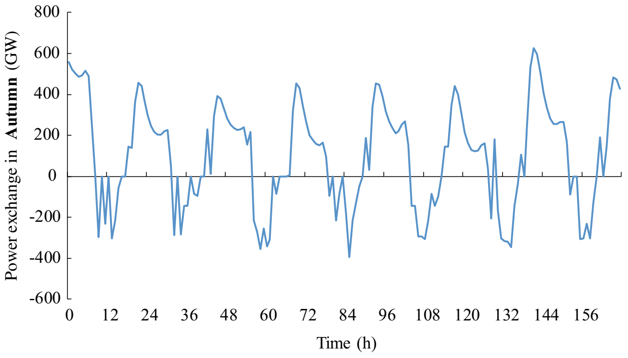

Fig. 2 Power exchange between CN and EU in Autumn for Case 4

The load factors of the transmission lines connecting CN and EU are given in Table 9. The annual and seasonal energy exchanges between CN and EU are given in Table 10. CN-EU denotes the power transfer from CN to EU while EU-CN denotes power transfer from EU to CN.

Table 9 Load factors of transmission lines

Case	Spring	Summer	Autumn	Winter	Annual
3	29.36%	28.34%	26.50%	35.11%	29.83%
4	17.11%	17.44%	34.64%	17.50%	21.67%

Table 10 Annual and seasonal energy exchange between CN and EU (TWh)

Season	Case 3		Case 4	
	CN-EU	EU-CN	CN-EU	EU-CN
Spring	95.27	64.56	18.93	220.56
Summer	70.57	85.42	76.06	170.74
Autumn	100.87	46.58	135.09	360.56
Winter	82.65	112.69	36.28	214.12
Annual	349.36	309.25	266.36	965.99

4.3.3 Sensitivity analysis

It is essential to conduct sensitivity analysis to show the robustness of the facility investment. The varying trends of the annual additional costs and line capacities with the increasing values of the key parameters are analyzed. For *Case 3*, the key parameters are the storage cost per kWh and line cost per km. The optimization studies were conducted under different settings with the costs per unit varying from 0.1x to 1x of their current values, with an increasing interval of 0.1x. For *Case 4*, the RE cost per kW and line cost per km are the key parameters, ranging from 0.1x to 1x of their current values with an increasing interval of 0.1x. The results of the sensitivity analysis are shown in Fig. 3 and 4 for *Case 3* and in Fig. 5 and 6 for *Case 4*.

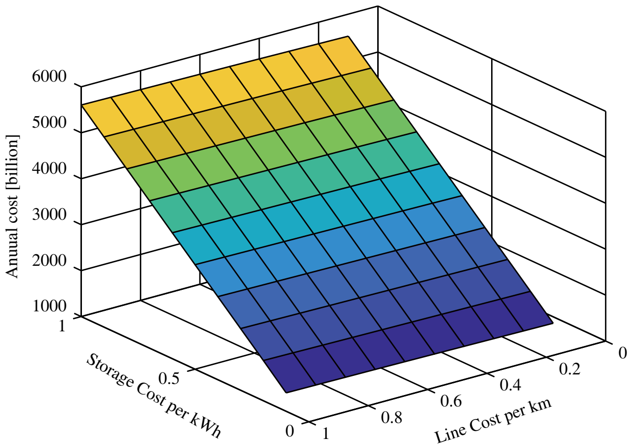

Fig. 3 Annual additional cost under varying energy storage and line cost per unit

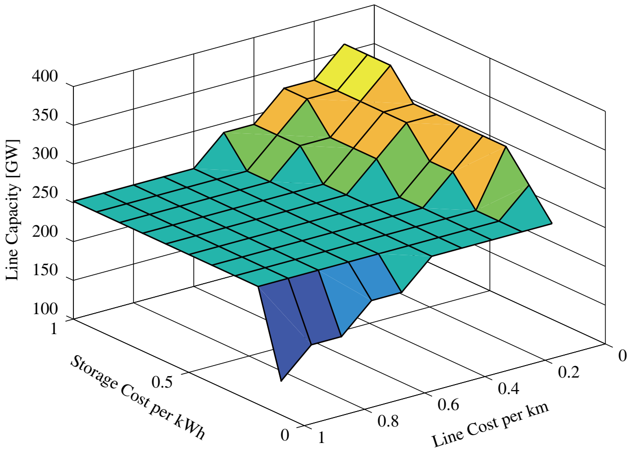

Fig. 4 Line capacity under varying energy storage and line cost per unit

It can be seen from Fig. 3 that the annual additional cost increases considerably with the increasing storage cost at a certain line cost per kW, while it grows slowly with the increasing line cost because the investment in lines takes up much lower share in the total annual additional cost than that for storage. There is no significant variation in the annual additional cost on increasing one key parameter and holding another parameter constant. The reason is as follows: Despite the time difference between CN and EU, there are still some periods when it is night in both areas (1:00 am to 8:00 am in CN) or the generation outputs of RE are both low; hence, the hourly power balance relies heavily on storage rather than passive lines and the small amount of the additional RE capacity installed. As the capacity for essential storage is already large enough, its variation following the variable cost per kWh is minor so that the investment cost of energy storage that accounts for a high share in the total cost changes smoothly.

Fig.4 shows that at a certain level of storage cost per kWh, the line capacity initially decreases when the line cost per km increases. The line capacity remains unchanged for storage costs higher than 0.2 times while it further decreases if the storage cost is extremely low i.e., less than 0.2 times. The higher the storage cost, the greater the distance for which the line capacity is kept unchanged, when the line cost increases and the storage cost is held constant. In general, when the storage cost is higher than 0.2 times and the line cost is higher than 0.5 times, the line capacity will

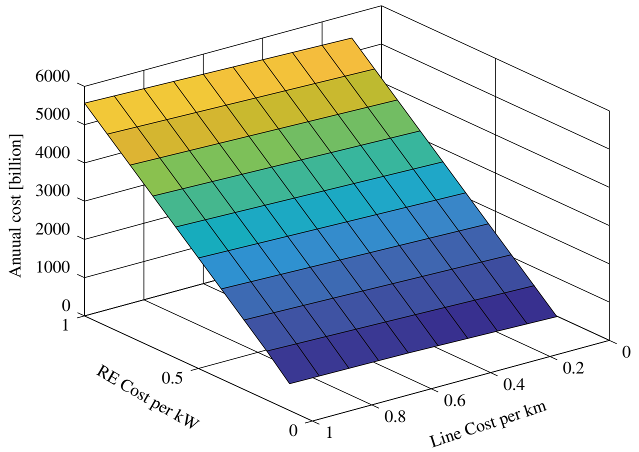

Fig. 5 Annual additional cost under varying RE and line cost per unit

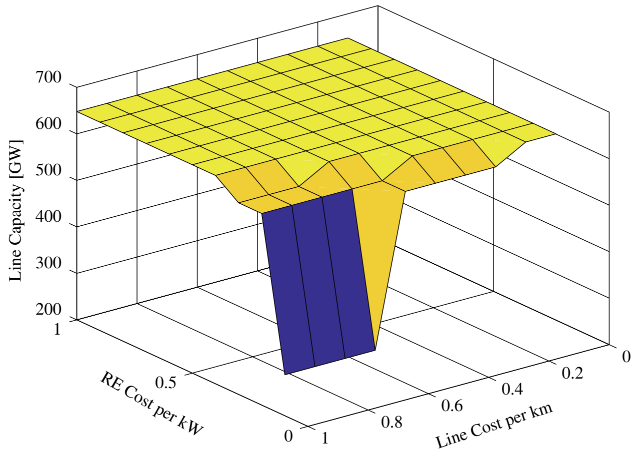

Fig. 6 Line capacity under varying RE and line cost per unit

become nearly stable, which demonstrates the rationality of the proposed line capacity.

It is revealed in Fig. 5 that the increase in the annual additional cost with the growth of RE cost per kW is more obvious than that with the growth of the line cost per km when another key parameter is set to a certain value (e.g., 1x of line cost and 1x of RE cost, respectively). This is because the cost of installing RE capacity takes up a high percentage of the total annual additional cost. Moreover, the variations in the annual additional costs during the above two processes are smooth, without significant sensitivity. Because the RE capacity needed to guarantee power balance in any period, including extreme situations of high demand and low availability of natural resources, is already high, its change with the varying RE cost per kW is small, leading to the above phenomenon.

As shown in Fig. 6, the line capacity is nearly unchanged except that the RE cost per kW is extremely low (smaller than 0.2 times), and the line cost per km is relatively high (higher than 0.6 times). The probability of the above situation is low, which demonstrates that the recommended capacities of lines are mostly optimal regardless of the variations in RE and line costs per unit.

5 Conclusions

In this paper, the economic benefits of interconnecting the power grids of China and EU together are discussed considering 100% RE generation for both power grids. The MILP optimization model for the investment considering the options of UHVDC transmission links, energy storage, and additional RE capacity is proposed. The sensitivities of annual costs and line capacities to the increasing values of several key parameters are analyzed. The following major conclusions can be drawn.

(1) Electricity interconnection between CN and EU decreases the annual additional costs by more than 30% when compared to the absence of interconnection, which demonstrates the necessity and benefits of CN-EU electricity interconnection.

(2) The investments in ±1100 kV UHVDC lines account for a small share in the total annual additional costs when using either energy storage or additional RE capacity to achieve hourly power balance, which are approximately 1.50% and 3.88%, respectively.

(3) The results of sensitivity analysis show the strong robustness of the proposed investment schemes as well as line capacities when using either energy storage or additional RE capacity to achieve hourly power balance.

Application of the proposed approach in the economic benefit analysis of other regional electricity interconnections will be of grate interest in the future work.

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(Editor Zhou Zhou)