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Calculation of Total Carbon Emission Capability of Integrated Energy Systems for Safe Operation

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ABSTRACT

With the integrated energy system (IES) that considers multi-energy complementarity and energy cascade utilization becoming an important trend in energy innovation, aiming at the current IES carbon emission reduction task and safe and stable operation requirements, accurately solving the maximum carbon emission capacity under the safe operation of IES can warn the working state of the system and provide references for carbon emission reduction tasks. Firstly, the steady-state IES energy flow and carbon flow model of electric-gas coupling is established. On this basis, the calculation model of IES maximum carbon emission capacity was established. Then, the mathematical model of IES carbon emission capacity curve is established. Finally, a numerical example is given to verify the effectiveness of the proposed model.

Keywords: Integrated energy systems; Multi-energy complementarity; Energy hub; Total carbon emission capability

NONMENCLATURE

Abbreviations	
IES	Integrated Energy System
TCE	Total Carbon Emission Capacity
TSC	Total Supply Capacity
GT	Gas Turbine
Symbols	
$R_{\mathrm{g},p}$	Carbon Flow Rate of Gas Pipeline
$E_{\mathrm{g},i}$	Carbon Potential of Gas Node
$R_{\mathrm{e},l}$	Carbon Flow Rate of Power Branch
$E_{\mathrm{e},i}$	Carbon Potential of Power Node
P_{GT}	Active Power Output of Gas Turbine
E_{GT}	Carbon Emission Intensity of Gas Turbine
$E_{\mathrm{EN},i}$	Carbon Flow Rate of Power Load
$E_{\mathrm{GN},i}$	Carbon Flow Rate of Gas Load

1. INTRODUCTION

With the advocacy of green and low-carbon development pathways, the integrated energy system (IES) faces more challenges and pressure under high proportion of new energy integration. Safety is the top priority for the planning and operation of the IES, and it is also a bottleneck restricting the efficient operation and high proportion of new energy integration. Based on ensuring system safety, accurately solving the total carbon emission capacity (TCE) of the IES is of great significance for further research on the low-carbon and safe operation strategies of the IES, and for promoting the green and low-carbon development of the energy industry.

Currently, there have been many scholars who have studied the total supply capacity (TSC) of the transmission grid[1], the distribution grid[2], and the IES[3], and built a research system based on energy flow for the TSC of the system. However, there has been little research on the mechanism of carbon emissions changes under the premise of system safety. The literature [4] proposed a power system energy flow safety-based model and calculation method for the carbon flow constraint-considered electric power system energy-carbon safety domain, and obtained the TSC of the power system. The literature [5] considered the integration of hydrogen into the power system and proposed a concept of fixed carbon emission domain for the electrical and hydrogen load coupling system under the constraint of carbon emissions, which depicted the operating space of the load under the constraints of safety and carbon emissions, reflecting the operating relationship between electric and hydrogen loads. None of the above studies provide a complete picture of the changes in system carbon emissions. Compared with the TSC analysis method, the TCE research can provide more comprehensive carbon emission safety information and

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provide reference data for dispatchers on carbon emissions.

IES refers to the coupling and coordination of multiple energy forms to achieve energy efficient use and interconnection of systems, whose direct energy sources are electricity, gas and new energy sources such as wind and light. The carbon emissions generated by IES are derived from the potential carbon dioxide emissions of the energy on the input side. Therefore, from the perspective of energy input, the electric-gas coupling system under new energy access is selected as a typical IES system for analysis in this TCE study.

In summary, this paper aims to study the change of system carbon emission capacity under the constraint of IES energy use security. Firstly, the steady-state IES energy flow and carbon flow model of electric-gas coupling is established. Secondly, the calculation model of IES total carbon emission capacity is established. Then, the mathematical model of IES carbon emission capacity curve is established. Finally, the carbon emission capacity curve is obtained by solving an example, and its highest point is the value of the maximum of total carbon emission capacity calculation model, which verifies the effectiveness of the proposed model.

2. STEADY-STATE ENERGY AND CARBON FLOW MODEL FOR ELECTRIC-GAS COUPLED

2.1 Steady-state energy flow model for natural gas pipeline network

The steady-state balance equation of natural gas in IES steady-state energy flow and carbon flow model coupled with electricity and gas is based on the Panhandle 'A' equation and the Weymouth equation[6] for high-pressure natural gas transmission pipeline network, which can be expressed as follows:

$$P_i^2 - P_j^2 = K_{\mathrm{g}} \cdot v_{\mathrm{g}} \cdot \left| v_{\mathrm{g}}{}^{0.854} \right| \tag{1}$$

$$K_{\mathrm{g}} = 18.43 \cdot L_{\mathrm{g}} / (\varepsilon^2 D_{\mathrm{g}}^{4.854}) \tag{2}$$

which P_i^2 and P_j^2 represent the square of the injected pressures at nodes *i* and *j*, respectively. v_{g} is the natural gas flow rate in the pipeline. K_{g} is the pipeline constant. L_{g} is the pipeline length. ε is the pipeline efficiency coefficient. D_{g} is the pipeline diameter.

This paper adopts gas-driven compressors to compensate for pressure losses caused by long-distance transmission in gas systems. The energy flow model can be represented as follows:

$$\kappa_p = \xi_1 + \xi_2 P_{\mathrm{co},p} + \xi_3 P_{\mathrm{co},p}^2 \tag{3}$$

$$P_{\mathrm{co},p} = T_{\mathrm{g},p} F_{\mathrm{co},p} \left[\left(\Pi_{\mathrm{out}} / \Pi_{\mathrm{in}} \right)^{H_{\mathrm{g},p}/2} - 1 \right] \tag{4}$$

which κ_p represents the natural gas consumption of the compressor in pipeline *p*, ξ_{1-3} is the energy conversion efficiency constant, $P_{\mathrm{co},p}$ is the power required by the compressor, Π_{out} is the square of the compressor outlet pressure, Π_{in} is the square of the compressor inlet pressure, $F_{\mathrm{co},p}$ is the inlet flow rate of the compressor, and $T_{\mathrm{g},p}$ and $H_{\mathrm{g},p}$ are power conversion constants for pipeline *p*.

2.2 Steady-state carbon flow model for natural gas pipeline network

The steady-state carbon flow model for the natural gas pipeline network can be expressed as follows:

$$R_{\mathrm{g},p} = E_i (F_{\mathrm{g},p} + \kappa_p) c_{\mathrm{al},m} \tag{5}$$

$$E_{\mathrm{g},i} = \frac{\sum_{p=1}^{G_{\mathrm{num,n}}} (F_{\mathrm{g},p} + \kappa_p) c_{\mathrm{al},m} \rho_{i,p} + \sum_{m=1}^{S_{\mathrm{num,g}}} F_{\mathrm{out},m} c_{\mathrm{al},m} E_{i,m}}{\sum_{p=1}^{G_{\mathrm{num,n}}} F_{\mathrm{g},p} c_{\mathrm{al},m} + \sum_{m=1}^{S_{\mathrm{num,g}}} F_{\mathrm{out},m} c_{\mathrm{al},m}} \tag{6}$$

which $R_{\mathrm{g},p}$ represents the carbon flow rate of gas pipeline *p*, $E_{\mathrm{g},i}$ is the carbon potential at node *i*, $F_{\mathrm{g},p}$ is the gas flow rate in pipeline *p*, $G_{\mathrm{num,n}}$ and $S_{\mathrm{num,g}}$ represent the number of other connected nodes and natural gas stations at node *i*, respectively. $\rho_{i,p}$ represents the carbon flow density of pipeline p connecting node *i*. $E_{i,m}$, $F_{\mathrm{out},m}$, and $c_{\mathrm{al},m}$ represent the carbon potential, output gas flow rate, and output gas heating value of the natural gas station *m* connected to node *i*.

2.3 Steady-state energy and carbon flow model for power systems

The steady-state energy flow model for power systems adopts the commonly used AC power flow balance equations. Carbon emissions in the power system primarily originate from conventional energy sources such as thermal power generation and gas power generation. Based on the theory of carbon emission flow in the power system, the steady-state carbon flow model distributes carbon emissions to loads and branches. The model is represented as follows:

$$R_{\mathrm{e},l} = E_{\mathrm{e},i} (P_l + \sigma_l) \tag{7}$$

$$E_{\mathrm{e},i}=\frac{\sum_{l=1}^{N_{\mathrm{num,n}}}(P_l+\sigma_l)\delta_l+\sum_{n=1}^{E_{\mathrm{num,e}}}P_{\mathrm{G},n}E_{\mathrm{G},n}}{\sum_{l=1}^{N_{\mathrm{num,n}}}P_l+\sum_{n=1}^{E_{\mathrm{num,e}}}P_{\mathrm{G},n}} \tag{8}$$

which $R_{\mathrm{e},l}$ and $E_{\mathrm{e},i}$ represent the carbon flow rate of power branch *l* and the carbon potential at node *i*, respectively. P_l and σ_l represent the active power and corresponding loss power of branch *l*. $N_{\mathrm{num,n}}$ and $E_{\mathrm{num,e}}$ represent the number of other connected nodes and generator units at node *i*, respectively. δ_l represents the carbon flow density of branch *l* connecting node *i*. $P_{\mathrm{G},n}$ and $E_{\mathrm{G},n}$ represent the output power and emission intensity of the generator unit *n* connected to node *i*.

2.4 Energy and carbon flow models for electromechanical coupling components

Coupling components in IES achieve heterogeneous energy conversion while also altering the distribution of carbon emission flow. The IES system studied in this paper mainly consists of gas-consuming power coupling components, with gas turbine (GT) as an example. The gas consumption of GT can be calculated based on the output power and the heating value of the input gas. The energy conversion equation is as follows:

$$\begin{aligned}P_{\mathrm{GT}}&=\eta_{\mathrm{GT}}\left(F_{\mathrm{GT}}\right)F_{\mathrm{GT}}c_{\mathrm{al,GT}}\\&=\left(\alpha F_{\mathrm{GT}}^3+\beta F_{\mathrm{GT}}^2+\gamma F_{\mathrm{GT}}\right)c_{\mathrm{al,GT}}\end{aligned} \tag{9}$$

which P_{GT} represents the active power output of the GT. F_{GT} is the natural gas flow rate entering the GT. $\eta_{\mathrm{GT}}\left(F_{\mathrm{GT}}\right)$ is the efficiency function of the GT. α, β, and γ are the gas consumption coefficients of the GT. Q_heat is the heating value of the natural gas input to the GT.

Carbon emissions generated by GT power generation come from the potential carbon dioxide emissions of natural gas consumed. Therefore, the carbon emission model of GT is expressed as follows:

$$E_{\mathrm{GT}}=(F_{\mathrm{GT}}c_{\mathrm{al,GT}}/P_{\mathrm{GT}})\cdot E_{\mathrm{g},i} \tag{10}$$

which E_{GT} represents the emission intensity of carbon for the GT unit, corresponding to the carbon potential at the node where the unit is connected.

2.5 Load carbon flow rate

After calculating the carbon potential of the load node, the carbon flow rate of the load node can be expressed as follows:

$$E_{\mathrm{EN},i}=P_{\mathrm{e},i}E_{\mathrm{e},i} \tag{11}$$

$$E_{\mathrm{GN},i}=P_{\mathrm{g},i}E_{\mathrm{g},i} \tag{12}$$

which $E_{\mathrm{EN},i}$ represents load carbon flow rate of the power load. $E_{\mathrm{GN},i}$ represents load carbon flow rate of the gas load. $P_{\mathrm{e},i}$ and $P_{\mathrm{g},i}$ represents the electric load and the gas load respectively.

3. DEFINITION AND MODEL OF TOTAL CARBON EMISSION CAPACITY IN IES

3.1 Operating point of total carbon emission capacity

In this paper, total carbon emission capacity refers to all carbon dioxide emissions per unit time of the system under the constraint of IES meeting the current operating safety index in a certain energy supply area. The minimum set of state variables for the safe operation of a system is called the carbon emission capacity operating point. In this paper, the GT unit is regarded as the gas load, and its state variable is the gas flow of the corresponding gas supply node. Assuming that the IES includes generator set, electric load, air source gate, gas load and gas turbine, then the operating point of the system can be represented as a set of vectors as follows:

$$\begin{aligned}\boldsymbol{W}_{s,\mathrm{IES}}=[\,&P_{\mathrm{E},1},\cdots,P_{\mathrm{E},n},\cdots,P_{\mathrm{E},X_{\mathrm{e}}-X_{\mathrm{gt}}-1},\\&P_{\mathrm{load},1},\cdots,P_{\mathrm{load},k},\cdots,P_{\mathrm{load},X_{\mathrm{e,load}}},\\&F_{\mathrm{gas},1}^{\mathrm{sta}},\cdots,F_{\mathrm{gas},m}^{\mathrm{sta}},\cdots,F_{\mathrm{gas},X_{\mathrm{gas}}-1}^{\mathrm{sta}},\\&F_{\mathrm{gas},1},\cdots,F_{\mathrm{gas},t},\cdots,F_{\mathrm{gas},X_{\mathrm{g,load}}-X_{\mathrm{gt}}},\\&F_{\mathrm{gt},1},\cdots,F_{\mathrm{gt},s},\cdots,F_{\mathrm{gt},X_{\mathrm{gt}}}\ ]\end{aligned} \tag{13}$$

which $\boldsymbol{W}_{s,\mathrm{IES}}$ represents the set of state variables at the operating point. X_{e}, $X_{\mathrm{e,load}}$, X_{gas}, $X_{\mathrm{g,load}}$ and X_{gt} represent the number of generator units, electrical loads, gas source gate stations, gas loads and gas turbines, respectively. $P_{E,n}$ represents the output power of the generator, where *n* ranges from 0 to X_{e}-X_{gt}-1. $P_{\mathrm{load},k}$ represents the power of the electrical load, where *k* ranges from 0 to $X_{\mathrm{e,load}}$. $F_{\mathrm{gas},m}^{\mathrm{sta}}$ represents the gas flow rate at the mth natural gas gate station, where m ranges from 0 to X_{gas}-1. $F_{\mathrm{gas},t}$ represents the flow rate of the gas load, where *t* ranges from 0 to $X_{\mathrm{g,load}}$-X_{gt}. $F_{\mathrm{gt},s}$ represents the input gas flow rate of the gas turbine *s*.

3.2 Definition and Model of Maximum Carbon Emission Capacity

The maximum of total carbon emission capacity in the IES, denoted as TCE$_{\max}$, which can be represented as follows:

$$\begin{cases} \mathrm{TCE}_{\max} = \max(\sum_{i}^{N_{\mathrm{EN}}} E_{\mathrm{EN},i} + \sum_{j}^{N_{\mathrm{GN}}} E_{\mathrm{GN},j}) \\ \text{s.t.} \quad \boldsymbol{h}(\boldsymbol{W}_s) = 0 \\ \qquad \boldsymbol{g}(\boldsymbol{W}_s) \le 0 \end{cases} \tag{14}$$

which TCE$_{\max}$ represents the maximum carbon emission capacity limit in the IES. N_{EN} and N_{GN} represent the total number of load nodes in the EN and GN respectively.

$\boldsymbol{h}(\boldsymbol{W}_s)$ mainly includes the EN power flow balance equation, GN steady energy flow balance equation, carbon emission flow balance equation, energy conversion balance equation of coupling element and carbon emission input and output balance equation.

$\boldsymbol{g}(\boldsymbol{W}_s)$ mainly includes three parts, which can be represented as follows:

$$\begin{cases} \boldsymbol{g}(\boldsymbol{W}_{\boldsymbol{s}}) = \{\boldsymbol{H}_{\mathrm{EN}}, \boldsymbol{H}_{\mathrm{GN}}, \boldsymbol{H}_{\mathrm{GT}}\} \\ \boldsymbol{H}_{\mathrm{EN}} = \begin{cases} \boldsymbol{V}_{\mathrm{E},i}^{\min} \le \boldsymbol{V}_{\mathrm{E},i} \le \boldsymbol{V}_{\mathrm{E},i}^{\max} \\ \boldsymbol{\theta}_{\mathrm{E},l}^{\min} \le \boldsymbol{\theta}_{\mathrm{E},l} \le \boldsymbol{\theta}_{\mathrm{E},l}^{\max} \\ \boldsymbol{P}_{\mathrm{E},l} \le \boldsymbol{P}_{\mathrm{E},l}^{\max} \\ \boldsymbol{P}_{\mathrm{E,G}}^{\min} \le \boldsymbol{P}_{\mathrm{E,G}} \le \boldsymbol{P}_{\mathrm{E,G}}^{\max} \end{cases} \\ \boldsymbol{H}_{\mathrm{GN}} = \begin{cases} \boldsymbol{p}_{\mathrm{gas},j}^{\min} \le \boldsymbol{p}_{\mathrm{gas},j} \le \boldsymbol{p}_{\mathrm{gas},j}^{\max} \\ \boldsymbol{g}_{\mathrm{gas},j}^{\min} \le \boldsymbol{g}_{\mathrm{gas},j} \le \boldsymbol{g}_{\mathrm{gas},j}^{\max} \\ \boldsymbol{F}_{\mathrm{gas},j} \le \boldsymbol{F}_{\mathrm{gas},j}^{\max} \\ \boldsymbol{K}_{\mathrm{gas,co}}^{\min} \le \boldsymbol{K}_{\mathrm{gas,co}} \le \boldsymbol{K}_{\mathrm{gas,co}}^{\max} \end{cases} \\ \boldsymbol{H}_{\mathrm{E}}^{\mathrm{EGH}} = \{\boldsymbol{P}_{\mathrm{E,GT}} \le \boldsymbol{P}_{\mathrm{E,GT}}^{\max} \end{cases} \tag{15}$$

which, $\boldsymbol{H}_{\mathrm{EN}}$ is the safe operation inequality constraint set, $\boldsymbol{H}_{\mathrm{GN}}$ is the safe operation inequality constraint set, $\boldsymbol{H}_{\mathrm{GT}}$ is the safe operation inequality constraint set of coupling link, $\boldsymbol{V}_{\mathrm{E},i}$ is the EN node voltage column vector; $\boldsymbol{\theta}_{\mathrm{E},l}$ is the branch phase angle difference column vector; $\boldsymbol{P}_{\mathrm{E},l}$ is the matrix of active power flow distribution for branches. $\boldsymbol{P}_{\mathrm{E,G}}$ is the matrix of injected power distribution for generators. $\boldsymbol{p}_{\mathrm{gas},j}$ is the pressure column vector of GN node; $\boldsymbol{g}_{\mathrm{gas},j}$ is the matrix of flow distribution for GN branches; $\boldsymbol{K}_{\mathrm{gas,co}}$ is the column vector of compressor compression ratio; $\boldsymbol{P}_{\mathrm{E,GT}}$ is the column vector of electrical power output for GT.

4. TOTAL CARBON EMISSION CAPACITY CURVE MODEL

TCE$_{\max}$ represents the maximum carbon emission capacity limit of IES under specific operating conditions. In comparison, the carbon emission capacity curve (TCE curve) can provide a comprehensive description of the system's carbon emission capacity. Therefore, to fully describe the IES carbon emission capacity limit under N-0 safety constraints, this paper defines the TCE curve as follows:The TCE curve is formed by arranging the total carbon emission capacities of all operating points corresponding to the critical safety operating states of IES in ascending order. The horizontal axis represents the sampling points. The TCE curve's highest point corresponds to the maximum carbon emission capacity point, TCE$_{\max}$, while the lowest point represents the minimum carbon emission capacity point, TCE$_{\min}$. The intermediate points on the TCE curve represent the carbon emission capacities of the system under different operating modes. The mathematical model of the TCE curve is represented as follows:

$$\mathrm{TCE}_{\mathrm{curve}} = \left\{ (i, \mathrm{val}(C_i)) \left| \begin{array}{l} \mathrm{val}(C_i) \le \mathrm{val}(C_{i+1}) \\ C_i \in \partial \boldsymbol{\Omega}_{st} \\ i \in \{1,2,3\cdots\} \end{array} \right. \right\} \tag{16}$$

which, $(i, \mathrm{val}(C_i))$ represents a point on the TCE curve, where i represents the sampling number. $\mathrm{val}(C_i)$ represents the total carbon emission capacity of the system. $\boldsymbol{\Omega}_{st}$ represents the strict critical boundary that the system needs to satisfy, which refers to the constraints mentioned in equation (14).

Since the operating points in the system are infinite, the sampling algorithm [7] is adopted to generate a finite number of samples that can represent the complete boundary points, and TCE curves are drawn based on the sample data.

5. CASE STUDY

5.1 Study settings

The IES case study topology used in this paper is illustrated in Figure 1. It is an IEEE 14-node power system that includes 5 generator units. Nodes Ne$_2$ and Ne$_6$ are coupled with gas loads Ng$_3$ and Ng$_4$ through GT$_1$ and GT$_2$, respectively. Ne$_1$ represents a thermal power generator unit, while Ne$_3$ and Ne$_8$ represent renewable energy generator units such as wind and solar.

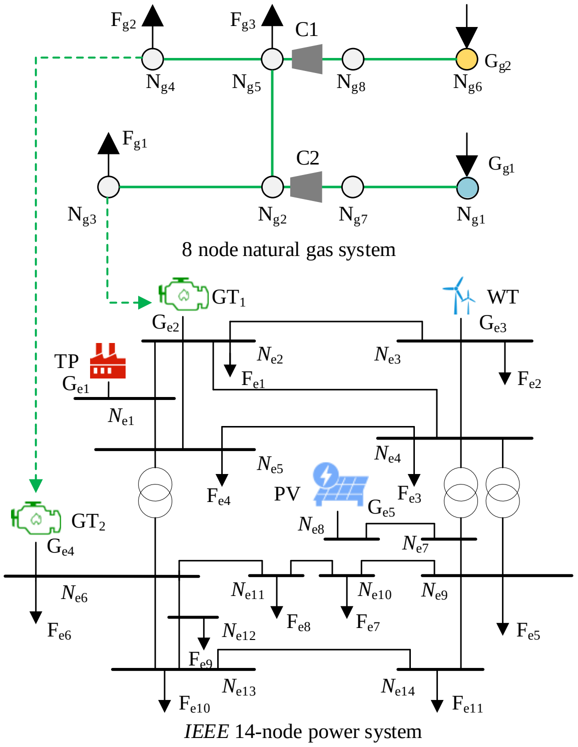

Figure 1. IES example structure diagram

5.2 *Analysis of TCE$_{max}$ and TCE Curve*

Through the aforementioned case study, as shown in Figure 2, similar to the maximum power supply capacity curve in a distribution system, an IES system also exhibits a carbon emission capacity curve. Compared to the single TCE$_{max}$ and TCE$_{min}$ evaluation indicators, the TCE curve reflects the comprehensive carbon emission capacity of the IES system under various operating conditions. The TSC curve reflects the system's power supply capacity limits under different load distributions, while the TCE curve reflects the carbon emission capacity levels of the system under different operating conditions. This provides a new perspective for carbon emission monitoring and warning in IES. Dispatch personnel can avoid the TCE$_{max}$ and TCE$_{min}$ points based on the current carbon emission level of the system, eliminating potential "safety" risks and making timely adjustments to the system's operation.

The TCE$_{max}$ value obtained by using the maximum carbon emission capacity model is 322.36tCO$_2$/h, which is the highest point of the TCE curve, which verifies the effectiveness of the model. Taking the TCE curve obtained from the case study in this paper as an example, similar to the distribution pattern of the traditional TSC curve, the TCE curve obtained from the case study shows a relatively flat shape without significant "steep slopes". This indicates that the IES system has a strong ability to adapt to changes in load distribution. The TCE curve exhibits a smooth segment near TCE$_{max}$ and TCE$_{min}$, indicating that the system has TCE$_{max}$ and TCE$_{min}$ points while ensuring the system's safe operating state. When the carbon emissions generated by the system exceed the TCE$_{max}$ point or fall below the TCE$_{min}$ point, it indicates that the system has deviated from the safety boundary and entered an abnormal operating state. Dispatch personnel need to promptly apply control measures.

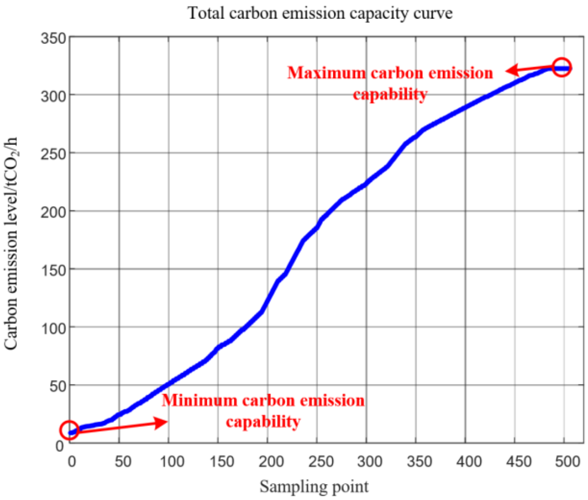

Figure 2. Total carbon emission capacity curve

6. CONCLUSIONS

Accurate calculation of the safety-oriented IES carbon emission capacity can provide an early warning system status. Based on this, this paper proposes a calculation model of IES total carbon emission capacity, characterizes the carbon emission capacity curve, and analyzes the early warning effect of TCE$_{max}$ and TCE$_{min}$ points on the curve on the safe operation of IES. It provides a method for the dispatcher to observe the safety of the system from the carbon emission level of the system. The next step is to verify the relationship between TCE and TSC, explore the distribution of TCE under the same TSC scenario, and help the clean and low-carbon development of IES.

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