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Analysis of transmission expansion planning considering consumption-based carbon emission accounting

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HIGHLIGHTS

- Calculation of virtual carbon emission flow and consumption side carbon emission.
- Transmission planning towards equity of consumption side carbon emission.
- Equity index of consumption side carbon emission to quantify transmission planning.

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ABSTRACT

Consumption-based carbon emission accounting is able to clarify consumers' responsibility for the carbon emissions from a power system. The responsible amount of carbon emissions for each consumer can be calculated based on the power consumption and the accordant carbon emission flow (CEF). Distribution of the CEF in the network may vary significantly under different transmission network configurations, resulting in different attributed carbon emission responsibilities of consumers. This paper describes how transmission expansion planning (TEP) and consumption-based carbon emission accounting affect each other. A novel TEP model considering the consumption-based carbon emission accounting is presented. A new index named CO_2 allocation equity coefficient (CAEC) is introduced to quantify the equity performance of the consumption-based carbon emission accounting system. As such, the requirement for different equity performances can be explicitly incorporated into the TEP model as a constraint to determine its effect on TEP. The proposed TEP model is tested on Garver's 6-bus system and a modified IEEE 39-bus system. The results show that the methodology is able to obtain the transmission expansion planning, in general, more lines must be planned to achieve better equity performance, with more even consumption-based carbon emission, but leading to an overall increasing tendency in the annualized transmission investment cost.

1. Introduction

Excessive CO_2 emission has attracted significant attention in recent years and posed great challenges to the sustainable development of human society [1]. As the largest source of CO_2 emissions, the electric power industry is now facing a major challenge in reducing CO_2 emissions. The power industry is susceptible to the "carbon lock-in" effect, that is, the CO_2 emission characteristics of a power system are difficult to change due to the long service life of generation units and transmission equipment [2]. Therefore, optimal planning is critical for the reduction of CO_2 emissions in power systems. CO_2 emissions can be incorporated into power system planning either as an additional cost in the objective function [3] or as an allowed emission inventory in the constraints [4,5]. Consideration of carbon emissions in the generation expansion planning (GEP) is rather straightforward because most CO_2 emissions in a power system are emitted during generation [2–8]. However, opinions differ on how TEP can be optimized to help reduce carbon emissions in power systems. In [9], the carbon emission costs incurred by generation were incorporated into the objective function of the TEP model, and line losses were considered in the load balance constraint. Carbon emissions that resulted from the manufacturing and construction of the transmission network were considered in [10]. In another study [11], it was suggested that TEP should be optimized to maximize the utilization of low-carbon power sources.

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Nomenclature

A. Indices

b	index of a bus
i	index of a generation unit
j	index of a typical day considered in TEP
k	index of an available corridor
l	index of a transmission line
t	index of an hour

B. Sets

NB	set of buses
NC	set of available corridors
NL	set of lines in the expanded network
NL_C	set of candidate transmission lines
NL_E	set of existing transmission lines
NG	set of generation units
ND	set of typical days considered in TEP
NT	set of hours per day for days in ND

C. Parameters

c_{Ll}	annualized investment cost of line l (per km·MW·year)
c_{gi}	unit generation cost of generation unit i
c_C	CO_2 emission tax rate
e_i^G	CO_2 emission intensity of generation unit i
n_b	number of load buses
s_l	length of line l
L_{bt}^j	load on bus b at time t for typical day j
$G_{i\min}/G_{i\max}$	minimum/maximum output of the ith generation unit
$\overline{P}_{l\max}$	maximum transmission capacity of line l
M	a very large number
$\overline{P}_l$	rated capacity of line l
T^j	duration of typical day j in a year
W_b	proportion of the load on bus b
X_l	reactance of transmission line l
H	maximum CAEC allowed

D. Variables

E_{Cb}	CO_2 emissions allocated to consumers on bus b
e_{bt}^{Bj}	nodal CEF intensity of bus b at time t for typical day j
$\bar{e}_b^B$	average nodal CEF intensity of bus b
G_{it}^j	output of generation unit i at time t for typical day j
I_l	binary variable indicating whether the candidate line l is put into operation
P_{lt}^j	active power flow on line l at time t for typical day j
θ_{lt}^j	the angle of bus b at time t for typical day j
PN_b	total active power injected into bus b
Y_b	proportion of CO_2 emission costs allocated to consumers on bus b
γ	CO_2 allocation equity coefficient

Most of the existing methods to account for CO_2 emissions in power systems are based on the generation side because CO_2 is directly emitted from generators [12]. However, generation-based carbon emission accounting may lead to unbalanced responsibilities and benefits between generation units and consumers. It may also cause carbon-leakage, especially in systems that have inter-area thermal power exchanges [13]. The "consumption-based" accounting perspective is considered to be fairer than the "generation-based" accounting perspective in attributing responsibility for CO_2 emissions, and it can avoid carbon leakage [14]. A tracing method to attribute CO_2 emissions to consumers was presented in [15]. In [16,17], the model of CEF was introduced to realize the same transition, and the CEF distribution in the power network of China was analyzed. Although there are differences in the definitions and techniques used in these studies, both of the proposed methods attribute carbon emissions to consumers based on the power flow tracing method [18], through which carbon emissions are attributed to consumers based on their power consumption behavior and the source of their consumed power. In this paper, the model of CEF is adopted to calculate consumption-based carbon emission in power systems. By attributing carbon emissions to consumers based on the tracing of power flows, the detailed generation and network configurations are properly considered in the model of CEF, which therefore provides a reasonable method for consumption-based accounting in power systems.

Equity is a key issue to consider when addressing CO_2 emission-related problems to ensure widespread participation and efficient CO_2 reduction. Inter-provincial carbon leakage due to the outsourcing of CO_2 within China was analyzed in [19], which identified an unequal allocation of emissions reduction responsibility under the current policies. The equity problem has also been considered in the allocation of carbon emission quotas [14,20]. The electricity consumed by different consumers in a power system is homogenous and cannot be uniquely attributed when mixed; therefore, the problem of equity should be further considered based on the model of CEF when consumption-based accounting is adopted.

Power flow in the transmission system depends significantly on the network configuration. Power flow distributions under different TEP schemes differ, which can lead to different carbon emission allocation results among consumers based on the model of CEF. Thus, paying attention to the allocation results will have a considerable impact on TEP. This paper studies how consumption-based carbon emission accounting and its related equity performance will affect TEP. We will also show that different TEP schemes may lead to different carbon emission cost allocations among consumers based on CEF. Based on the definition of CAEC, the equity performance of the consumption-based carbon emission allocation is quantified and incorporated into the TEP model as a constraint. Two case studies based on Garver's 6-bus system and a modified IEEE 39-bus system are investigated to verify the proposed TEP model. Cases that have different equity requirements are tested to analyze the mutual influence of the consumption-based carbon emission accounting and TEP.

It should be noted that TEP with consumption-based carbon accounting is the major objective of this paper, so comparison with traditional TEP is not included.

The major contributions of this paper are summarized as follows:

(1) A method of consumption-based carbon emission accounting based on the model of CEF is developed. The proposed method accounts for the carbon emission of power system from the consumption-based perspective by calculating the CEF of the network. It is capable of attributing carbon emission to consumers based on their power consumption behavior.
(2) The new index of CAEC is defined to quantify the equity performance of consumption-based carbon emission accounting.
(3) The model of TEP considering consumption-based carbon emission accounting is formulated. Effects of the equity constraint of the consumption-based carbon emission accounting on TEP are analyzed in detail.