Applied Energy 169 (2016) 363–369

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Application of 'potential carbon' in energy planning with carbon emission constraints

Dongwei Yu [a,b,*], Hongwei Tan [b]

[a] AVIC Center of Energy-efficient Technology Research and Development, 23 Anningzhuang Road, Beijing 100085, China
[b] Research Center of Green Building and New Energy, Tongji University, 1239 Siping Road, Shanghai 200092, China

HIGHLIGHTS

- A concept 'potential carbon' is presented.
- The application in energy planning is studied.
- Physical mechanism of carbon-related balance is introduced.
- Matching between energy sources and energy use is considered.

ARTICLE INFO

Article history:
Received 25 November 2015
Received in revised form 29 January 2016
Accepted 30 January 2016

Keywords:
Energy planning
Carbon emission constraints
Potential carbon
Critical carbon level

ABSTRACT

This paper puts forward a concept of 'potential carbon' and gives a definition analogous to potential energy. Potential carbon explains: (1) what is the driving force of the difference of carbon emissions, and (2) what is the position in the force field. On the basis, an approach about potential carbon analysis is developed to investigate a physical mechanism of carbon-related balance between energy supply and demand. Especially, a derived evaluation parameter of critical carbon level (CCL), which depends on availability of local energy sources and energy use profile, can reflect a geographical feature of a zone or zones in carbon-related balance. The proposed methodology is applied in a case of Haidian North region, Beijing. The result shows that potential carbon analysis is able to assist in making decisions on energy source planning to meet energy demand within carbon emission constraints.

1. Introduction

Energy planning is often conducted using integrated approaches that consider both the provision of energy supply and the role of energy efficiency in reducing demand. The traditional multi-criteria decision making (MCDM) methods [1–8] are widely applied in energy planning, the techniques provide solutions to the problem involving conflicting and multiple objectives. US Lawrence Berkeley National Laboratory has developed a DER-CAM model since 2000. The DER-CAM model is a mixed-integer linear program (MILP) originally written in the General Algebraic Modeling System (GAMS) [9]. The objective of the model is typically to minimize the cost for providing energy for individual customer sites or a μGrid, which is a semiautonomous grouping of generating sources (e.g. PV, solar thermal) and end-use sinks (e.g. electricity demand, heating and cooling demand) that are placed and operated in a coordinated way [10]. Stadler et al. [11] applied the DER-CAM model along with some accounting and simulation tools (e.g. RETScreen, EnergyPlus) to optimize distributed energy resources and building retrofits for the buildings at an Austrian Campus building. All of the above planning strategies are accustomed to establishing a target function for a region to meet the total demand with a set of constraints.

In light of increasingly stringent environmental regulations, some studies on low-carbon planning were conducted and characterized by introduction of low-carbon technologies and energy policies [12–16]. An energy and (or) environment systems model was usually developed to provide a quantitative vision of technology and management strategy options for effectively deploying energy efficiency and renewable energy for reducing the carbon footprint. The vision was termed a 'low-carbon society or city'.

Recently, researchers investigated the use of the pinch technology combined with optimization methods to generate heat exchanger network designs. The pinch technology was originally

* Corresponding author at: AVIC Center of Energy-efficient Technology Research and Development, 23 Anningzhuang Road, Beijing 100085, China. Tel.: +86 10 82183195; fax: +86 10 82183001.

E-mail address: 2009dwyu@tongji.edu.cn (D. Yu).

http://dx.doi.org/10.1016/j.apenergy.2016.01.127
0306-2619/

developed based on thermodynamic principles to identify optimal energy utilization strategies for process plants [17,18]. Linnhoff and Dhole [19,20] applied the pinch analysis in emissions targeting within a site of factories, which were supplied by an overall site utility system [21]. Tan and Foo [22] extended the emissions targeting into regional sectors, and used a graphical targeting procedure integrated with energy planning composite curves to minimize the amount of zero-carbon energy sources. Foo et al. [23] presented an algebraic targeting technique which overcame the visual resolution limitations of the graphical targeting tool. However, these targeting techniques were implemented on a condition that separate geographic regions shared a common energy source. For example, the needed energy of Regions I, II and III [22,23] was not categorized (only measured in primary energy equivalents) and met by a common source consisting of coal, oil and natural gas, followed by zero-carbon sources. In other words, locations of sources were not considered, and incompatibility of sources among the various regions was neglected. Lee et al. [24] refined and improved the technique and developed energy targets for different sub-sectors (i.e. industry and transportation) based on the cascade analysis concept. It turned out to be a partial solution to the incompatibility of sources in different places. In fact, the carbon emissions pinch analysis (CEPA) is actually an extension of traditional thermal and mass pinch analysis to the area of emissions targeting on a macro-scale [25,26]. It is unable to resolve the problem of the matching between energy supply and demand (i.e., three basic classifications: electricity, heating and cooling) in a micro-scale.

The objective of CEPA is to minimize the use of zero or low-carbon resources based on a source–sink superstructure model with a basic linear programming (LP) formulation. Pekala et al. [27] developed a flexible and expandable mathematical programming using the source–sink framework. The methodology was applied to optimum biofuels production with multiple footprints and deployment of carbon capture and storage retrofits with cost-effectiveness. A latest multistage inexact stochastic robust model was developed for regional energy system management with constraints of carbon and air pollutants to tackle uncertainties [28]. These mathematical programming approaches were established to meet the total energy demand at the least-cost or lowest environmental impact, but incapable of providing a solution to the problem of constraints of separate geographic regions.

Lam et al. [29] used a methodology known as Regional Resources Management Composite Curve (REC) to achieve minimum carbon footprint between various zones in a region. The REC algorithm generated a biomass exchange network, provided a view of energy and land availability in a region and displayed their trade-offs in a single plot. It was used to assess the priorities: either to produce and sell the surplus energy on the fuel market or use the land for other purposes such as food production. The methodology was used to identify biomass energy flow of zones, but it only considered one kind of energy (e.g. heating), and especially, it did not concern a given geographic constraint of carbon emissions.

One task of traditional energy planning is to obtain a possible balance between energy supply and demand at a least cost. If carbon emissions of a region are restricted, how is the energy planning performed? Under the constraint of carbon emissions, how is a supply-demand balance of energy (based on different classifications) developed? This paper puts forward a concept of 'potential carbon' which tries to address these problems in energy planning with carbon emission constraints.

The structure of this paper is as follows:

- Section 2 describes why and how to define 'potential carbon' analogous to 'potential energy 'and gives a calculation procedure of the 'potential carbon'.
- Section 3 describes the methodology. First, develop a carbon position table with geographic energy supply and demand of zones; second, perform integration by parts to obtain the potential carbon at a desired scale of space.
- In Section 4, a case study is used to illustrate how to implement energy planning based on the potential carbon theory.
- Section 5 summarizes advantages of the potential carbon analysis applied in energy planning with carbon emission constraints.

2. Definition of potential carbon

In physics, 'potential energy' is the energy that an object has due to its position in a force field or that a system has due to the configuration of its parts [30].

If the work for an applied force is independent of the path, then the work done by the force is evaluated at the start and end of the trajectory. This means that there is a function $U_{(x)}$, called a 'potential' that can be evaluated at the two points x_A and x_B to obtain the work over any trajectory between these two points. It is traditional to define this function with a negative sign so that positive work is a reduction in the potential, that is

$$W = \int_S F \cdot dx = U(x_A) - U(x_B) \tag{1}$$

where S is the trajectory taken from A to B. Because the work done is independent of the path taken, then this expression is true for any trajectory, S, from A to B.

Analogous to potential energy definition, 'potential carbon' is the net carbon emission that delivering of energy produces due to its carbon level (position) in an energy demand-supply field. The function of potential carbon is defined as

$$C = \int_S F \cdot dx = U(c_A) - U(c_B) \tag{2}$$

where S is the trajectory taken from A to B, and c_A and c_B are the corresponding carbon level (ton/TJ). The function $U_{(c)}$ is called the 'potential carbon' associated with 'F' of the applied force, which corresponds to energy demand or energy supply.

Potential carbon is formally positive in the energy demand side (Table 1), whereas negative in the supply side (Table 2). Suppose the total potential carbon of a region is negative, carbon emission of energy sources is within the carbon emission limit of a region. Otherwise, it exceeds the limit. Potential carbon reflects the degree of the interactions between the characteristics of energy sources and the environmental constraints.

Table 1
Integration by parts about potential carbon in the energy-demand side.

c_k	Δc_k	Energy demand	Potential carbon	Status description
c_{+1}			$D * \Delta c_{+1}$	Energy demand of D with a permitted carbon intensity of c_0 to be met by an energy source with an actual carbon factor of c_{+1}
	Δc_{+1}			
c_0		D	0 (baseline)	Energy demand of D with a permitted carbon intensity of c_0
	Δc_{-1}			
c_{-1}			$D * \Delta c_{-1}$	Energy demand of D with a permitted carbon intensity of c_0 to be met by an energy source with an actual carbon factor of c_{-1}

Note: $c_{+1} > c_0 > c_{-1}, \Delta c_{+1} = c_{+1} - c_0, \Delta c_{-1} = c_{-1} - c_0$.