ARTICLE IN PRESS

Applied Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Minimizing carbon footprint using pinch analysis: The case of regional renewable electricity planning in China

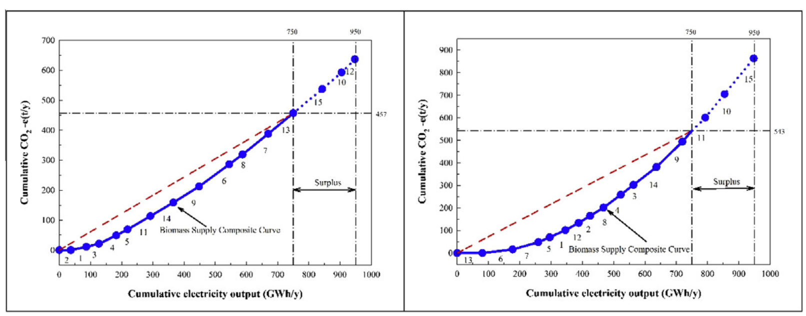
Zhiwei Li [a], Xiaoping Jia [a,*], Dominic C.Y. Foo [b], Raymond R. Tan [c]

[a] School of Environment and Safety Engineering, Qingdao University of Science and Technology, Qingdao 266042, China
[b] Department of Chemical and Environmental Engineering/Centre of Excellence for Green Technologies, University of Nottingham Malaysia, Broga Road, 43500 Semenyih, Selangor, Malaysia
[c] Chemical Engineering Department/Center for Engineering and Sustainable Development Research, De La Salle University, 2401 Taft Avenue, 0922 Manila, Philippines

HIGHLIGHTS

- Carbon-constrained regional renewable electricity planning is considered.
- The minimum renewable energy target is identified by pinch analysis.
- A two-step approach is proposed to synthesis an optimal biomass supply chain network.
- A case study based on a region in China illustrates the approach.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 29 February 2016
Received in revised form 29 April 2016
Accepted 3 May 2016
Available online xxxx

Keywords:
Pinch analysis
Renewable electricity
Carbon emission
Energy planning

ABSTRACT

Renewable energy has a more important role to play in China's power sector, especially at the regional level. Renewable electricity in China has made great progress on the basis of national policies. However, the promotion of renewable electricity sector at the regional level is still hampered by local issues. China needs to solve some challenging barriers related to implementation of polices for the development of renewable electricity. These barriers stem largely from availability and reliability constraints. Systematic planning techniques are needed to fully utilize abundant renewable energy resources. In this work, an improved graphical pinch analysis-based approach is presented, which considers carbon-constrained regional electricity planning and supply chain synthesis of biomass energy at the regional level in rural China. The minimum renewable energy target is identified by Carbon Emissions Pinch Analysis (CEPA). Next, a demand-driven approach is applied to synthesize the *biomass supply chain network* to meet the established target in a given region. A detailed case study of Laixi County in China is used to demonstrate the applicability of the proposed approach for policy-making to promote utilization of renewable electricity at the regional level.

1. Introduction

Emissions of greenhouse gases (GHGs) such as carbon dioxide (CO_2) from the energy sector are known to be among the major contributors to climate change [1]. Due to the global nature of the problem, every nation bears some degree of responsibility to enable shift toward a low-carbon developmental trajectory. Thus, more and more nations have undertaken policy measures to reduce emissions of GHGs. To achieve substantial reductions, measures such as energy efficiency enhancement and decarbonization of generation are among the key strategies used [2]. A low-carbon electricity generation structure is crucial to mitigate the "carbon

* Corresponding author.
E-mail addresses: cnlizhiwei@126.com (Z. Li), jiaxp@qust.edu.cn (X. Jia), dominic.foo@nottingham.edu.my (D.C.Y. Foo), raymond.tan@dlsu.edu.ph (R.R. Tan).

http://dx.doi.org/10.1016/j.apenergy.2016.05.031
0306-2619/

lock-in" effects in power sector, thus contributes to reduce CO_2 emission effectively and continuously for China [3]. Renewable energy sources will be used more extensively in the future combined heat and power based district heating systems [4]. It is estimated that for the scenario of maximum utilization of renewable energy large scale renewable energy development in 2050 will stimulate the output worth of $1.18 trillion and create 4.12 million jobs in China. In addition to economic benefit, it could substantially reduce the emissions of CO_2 and air pollutant such as NO_x, SO_2 [5]. Renewable electricity generation could supply 80% of U.S. generation in 2050. Achieving such high levels of renewable electricity results in that GHGs are reduced proportionally and water use is reduced by 50%. Also gross land-use impacts associated with renewable generation facilities, storage facilities, and transmission expansion total less than 3% of land area of the contiguous U.S. [6]. Hence, enhancing renewable electricity in the energy structure is necessary for China to achieve growth targets without undue growth in the level of emissions. As at the 2009 Copenhagen Climate Summit, China announced an ambitious CO_2 emissions reduction target: carbon intensity (amount of CO_2 emitted per unit of GDP) reduction by 40–45% of 2005 levels by year 2020. Furthermore, a secondary target of increasing the share of non-fossil sources to 15% of total primary energy consumption by year 2020 was also declared [7].

Historically, China's energy supply has been dominated by coal, which is cheap and abundant but has led to persistent problems with emissions. Energy demand in China will continue to increase at a rapid rate if the economy develops as in the past decades, and is projected to reach 4.7 billion tons of standard coal equivalent in 2020 [8]. At the same time, increased consciousness about climate issues has led to efforts to reduce emissions of GHGs. Hence, energy planning has to be done to enable sustainable growth along with progressive GHGs emission reduction. One promising option is to integrate renewable energies into the energy mix on a national or regional scale [9]. However, renewable energies are affected by the time of the day, the season and the weather, and this intermittency will surely affect the continuity and stability of the power supply [10]. The resource availability and geographical distribution of biomass byproducts in China are assessed in terms of crop residues, manure, forest and wood biomass byproducts, municipal waste and wastewater. It is estimated that the total quantity of crop residues, manure, forest and wood biomass byproducts, municipal waste and wastewater resource are 728, 3926, 2175, 155 and 48,240 Mt, respectively [11]. China can potentially produce about 174.4–248.6 million dry metric tons of crop residues per year when biomass prices are larger than $100 per metric ton. Rice straw is expected to account for about 47% of total residue production across the different biomass prices. Corn stover and wheat straw can contribute 28% and 25%, respectively, to total biomass production in China [12].

Recently, much research has been published on *carbon-constrained energy planning* based on *Pinch Analysis*. Pinch Analysis was originally developed as a systematic approach for optimizing energy use in industry, by taking into account thermodynamic principles to determine rigorous utility targets for process plants [13]. Based on the common principle of characterizing streams based on both quantity and quality, diverse applications of Pinch Analysis and *process integration* have emerged, such as *mass integration* [14], *water minimization* [15], refinery hydrogen network synthesis [16], etc. Links between energy efficiency gains and emissions reduction were first systematically addressed in a paper on the development of *total sites* methodology [17]. Key developments in this area are summarized in a review [18], while a recent paper describes directions for potential extensions of the methodology [19]. Meanwhile, major topics in process integration are available in a recently published handbook [20]. It is notable that Pinch Analysis methodology has continued to develop as a useful complementary approach to mathematical programming approaches due to its distinct advantage of facilitating decision-making insights [21].

Tan and Foo [22] first extended the use of Pinch Analysis into energy sector planning with carbon emission constraint. This procedure is now known as Carbon Emission Pinch Analysis (CEPA). One of the earliest application of CEPA was for the analysis of Irish electricity generation sector by Crilly and Zhelev [23]. CEPA is used to determine optimal energy resource mix by considering the entire demand of Ireland as a single sink without regional or sectoral disaggregation. Subsequently, an improved CEPA approach was designed to give more realistic energy and emissions targets for renewables of Irish electricity generation sector [24]. Atkins et al. [25] extended the CEPA approach to accounting for increased demand over long term planning horizon for the New Zealand electricity industry. The same group of researchers extended the use of CEPA for transportation sectors in New Zealand, in order to determine the feasibility of achieving the 1990 emission levels by 2050 [26]. Furthermore, CEPA is combined with Energy Return on Energy Investment (EROI) analysis to investigate the feasibility of New Zealand reaching and maintaining a renewables electricity target above 90% through to 2050 [27]. CEPA and EROI methodologies was also used to investigate energy planning for process heat application in New Zealand [28], as well as renewable electricity generation for the state of California in US [29]. Jia et al. [30] presented a detail planning and algebraic procedures for CEPA and was demonstrated by a case study of chemical industrial park. Results showed the proposed energy planning can cause a 10% reduction of CO_2 emission as compared with the original one. Also, many improvements of the approach have been reported in recent years. Foo et al. [31] proposed an algebraic method as an alternative to the original graphical approach. Also, alternative energy quality measures have been proposed such as land footprint [31], water footprint [32], *emergy transformity* [33], *energy return on investment* (EROI) [27] and inoperability risk [34]. A Multi-Dimensional Pinch Analysis approach to energy planning has also been recently developed, providing the optimal generation mix profile based on five important environmental footprints for China's power generation sector [35]. Yu and Tan [36] developed an approach about potential carbon analysis to investigate a physical mechanism of carbon-related balance between energy supply and demand. The result showed that this approach is able to assist in decision making on energy source planning to meet energy demand within carbon emission constraints. An overview of developments emerging from CEPA methodology is given in a review by Foo and Tan [37].

While these works focused on the use of Pinch Analysis for sector-scale energy planning, this methodology can also be used for the design of isolated electrical power generating units to electrify remote villages (where grid extension is often not feasible) Hence, many researchers have proposed various approaches to design a renewable hybrid power system. Sreeraj et al. [38] proposed a method to optimally size and to evaluate the cost of energy produced by a renewable hybrid power system. Battery bank as means of energy storage with different renewable energy systems is employed to enhance the system reliability and its overall performance [39]. Wan Alwi et al. [40] developed Power Pinch Analysis (PoPA) tools to determine the minimum target for outsourced electricity and the amount of excess electricity for storage during start up and normal operations. However, it does not consider the power losses in the system. Mohammad Rozali et al. [41] extended the PoPA method by considering the power losses that occur during the power system's conversion, transfer and storage. Wan Alwi et al. [42] introduced the heuristics for load shifting for the integrated hybrid power system. The results showed that up to 50% reduction in the maximum storage capacity and the maximum power demand is achieved. Ho et al. [43] proposed a novel approach

Please cite this article in press as: Li Z et al. Minimizing carbon footprint using pinch analysis: The case of regional renewable electricity planning in China. Appl Energy (2016), http://dx.doi.org/10.1016/j.apenergy.2016.05.031