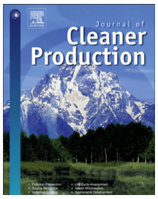
ARTICLE IN PRESS

Journal of Cleaner Production xxx (2015) 1–16

Contents lists available at ScienceDirect

Journal of Cleaner Production

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



Multi-dimensional pinch analysis for sustainable power generation sector planning in China

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

[a] *College 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*

ARTICLE INFO

Article history:
Received 29 March 2015
Received in revised form
23 October 2015
Accepted 23 October 2015
Available online xxx

Keywords:
Electricity generation
Power mix
Energy planning
Process integration
Pinch Analysis

ABSTRACT

Emerging economies account for a fast-growing share of the global energy market. In particular, energy use in China has become significant from both economic and environmental standpoints. This trend makes it necessary to balance the need for affordable, reliable electricity supply with the need to ensure that the power infrastructure is environmentally sustainable. As such, this paper presents a *multi-dimensional pinch analysis* (MDPA) of the power generation sector in China; the analysis considers five key indices: carbon footprint, energy return on investment (EROI), water footprint, land footprint, and risk to humans. By simultaneously quantifying five different indices under a common methodological framework, we are able to coherently assess the impact on five different environmental concerns. This approach provides a more complete picture of the true environmental impact of China's power sector. This information can thus help policymakers avoid the problem of shifting environmental impacts to other domains, which can occur when the analytic procedure used focuses on a single environmental dimension.

1. Introduction

Since the introduction of policy reforms in 1978, China has rapidly achieved significant socioeconomic progress, becoming the world's second-largest economy as of 2010 based on gross domestic product (GDP). This rapid economic growth, however, has been accompanied by a major increase in energy consumption. Between 2001 and 2012, China's total energy consumption grew from 44.08 EJ to 106.01 EJ (National Bureau of Statistics of China, 2013). However, the energy mix remained relatively unchanged. For example, coal accounted for approximately 66.6% of total primary energy consumption in 2012, barely lower than the 2001 level (68.3%), while the share of hydroelectric, nuclear, and wind power in energy consumption rose from 7.5% to 9.4% in the same period (National Bureau of Statistics of China, 2013). It will thus be a challenge for China to secure its energy supply in the coming decades in order to ensure sustainable development.

Total electricity generation in China in 2011 was reported at 4713.02 TWh, in which a vast majority of this output, i.e., 3833.70 TWh (81.3%) was generated from fossil fuel (primarily coal) (National Bureau of Statistics of China, 2013). Nuclear power generation was reported at 86.35 TWh (1.8%), while the remainder (16.9%) was from generated by renewable energy sources such as hydroelectric, wind, solar, and biomass (National Bureau of Statistics of China, 2013). By comparison, approximately 66.1% of total electricity in the United States (US) in 2011 was derived from fossil fuel, comprised of coal (68.1%), natural gas (30.4%), and oil (1.1%). Nuclear power and renewable sources accounted for 20.6% and 12.8%, respectively, of the total electricity (US Energy Information Administration, 2011). It is thus evident that coal plays a crucial role in electricity sector in China. Furthermore, in 2011, China's energy intensity per unit of growth was 0.27 toe (t of oil equivalent) per dollar, significantly worse than the world

---

[*] Corresponding author.

E-mail addresses: jiaxp@qust.edu.cn (X. Jia), cnlizhiwei@126.com (Z. Li), wangf@qust.edu.cn (F. Wang), Dominic.Foo@nottingham.edu.my (D.C.Y. Foo), raymond.tan@dlsu.edu.ph (R.R. Tan).

http://dx.doi.org/10.1016/j.jclepro.2015.10.102
0959-6526/© 2015 Elsevier Ltd. All rights reserved.

Please cite this article in press as: Jia, X., et al., Multi-dimensional pinch analysis for sustainable power generation sector planning in China, Journal of Cleaner Production (2015), http://dx.doi.org/10.1016/j.jclepro.2015.10.102

average of 0.19 toe/$, or the corresponding values for India (0.19 toe/$) and the US (0.17 toe/$) (IEA, 2013). This discrepancy suggests that significant reductions in energy intensity can be achieved using existing technologies.

According to the 12th Five-Year Plan for Energy Development of China (State Council of China, 2013), electricity generation capacity in 2015 is projected to increase to 1490 GW, whereas the installed coal-based electricity capacity is approximately 960 GW, covering about 64.4% of the total capacity. Hydroelectric power will contribute 290 GW (19.5%), and other sources will contribute the remaining of 16.1% (State Council of China, 2013). Under the “business as usual” scenario, China's energy demand will continue to increase rapidly, reaching 4.7 billion tons coal equivalent by 2020 (Fan and Xia, 2012). In the electricity sector, thermal power generation will reach 7258.83 TWh by 2020, and carbon emissions will reach 17,379.90 million tons (Liu et al., 2014a). On the other hand, in 2009 the Chinese government announced an ambitious carbon dioxide (CO_2) emissions reduction target: cutting carbon intensity (amount of CO_2 emitted per unit of GDP) by 40–45% of 2005 levels by 2020 (State Council of China, 2014). A secondary target is increasing the share of non-fossil sources to 15% of total primary energy consumption by 2020 (State Council of China, 2014). It is a matter of debate whether China can achieve these ambitious targets along with the growth in demand. It also raises the question of how energy consumption and emissions will evolve under different policy scenarios.

This paper presents a comprehensive analysis of the Chinese energy sector using graphical *multi-dimensional pinch analysis* (MDPA). This approach is an extension of classical pinch techniques used for various optimization applications, and in this work it allows different sustainability aspects to be considered in the context of power generation planning in China. Similar concepts have been applied in the New Zealand electricity sector (Walmsley et al., 2014) and transport sector (Walmsley et al., in press). It should be noted that this work uses a hierarchical analysis approach, as the development of a generalized pinch technique that simultaneously accounts for different quality measures remains an unsolved research problem (Tan et al., 2015). The rest of the paper is organized as follows. The following section describes the basic method used for this analysis, while Sections 3–7 present the results for the different footprints. For each footprint, these sections show comparative analysis with other countries, and also show long-term trend projections. Section 8 then discusses these results and their policy implications, and Section 9 concludes the paper and suggests prospects for further research.

2. Methodology and data

2.1. Footprint-constrained Pinch Analysis

Pinch Analysis is a systematic method originally developed for the synthesis of *heat exchanger networks* (HENs) in the 1970s (Hohmann, 1971). It was then extended for minimizing thermal energy consumption of industrial plants, specifically for identifying thermodynamically feasible energy budgets or “targets” (Smith, 1995). These targets serve as performance benchmarks, against which any energy conservation measures can be measured. The fundamental principle of Pinch Analysis is to define streams in terms of quantity (e.g., energy flows) and quality (e.g., temperature). The latter provides the driving force that defines directionality, since the flow of heat is defined by temperature gradient. After early energy conservation applications, different variants of Pinch Analysis have been developed by defining different quality and quantity indices. For example, El-Halwagi and Manousiothakis (1989) introduced mass pinch techniques based on the analogy between heat and mass transfer; their approach used mass flows and concentration levels as the measures of stream quantity and quality. Time has also been used as a quality index to characterize the flow of goods in temporally constrained activities. This extension has resulted in Pinch Analysis-based production planning problems, such as that for production supply chain (Singhvi and Shenoy, 2002), biomass allocation (Singhvi et al., 2004), equipment scheduling (Lim et al., 2014), human resource planning (Foo et al., 2010), and hybrid power systems design (Mohammad Rozali et al., 2014).

In addition, new applications of Pinch Analysis have been proposed where sustainability metrics are used as quality indices. Tan and Foo (2007) first proposed the use of Pinch Analysis for managing energy resources under carbon constraints. This approach, now known as *carbon emissions pinch analysis* (CEPA), has been utilized in a number of planning scenarios in different countries/regions, including New Zealand (Atkins et al., 2010), Ireland (Crilly and Zhelev, 2008), Poland (Pękala et al., 2010), and China (Jia et al., 2009). The methodology has since been extended to account for other measures of energy quality, such as *land footprint* (Foo et al., 2008), *water footprint* (Tan et al., 2009), *emergy transformity* (Bandyopadhyay et al., 2010), *inoperability risk* (Tan and Foo, 2013), and *energy return on investment* (EROI) (Walmsley et al., 2014). Such extensions are possible for scale-invariant sustainability metrics, which are compatible with the linearity assumptions used in Pinch Analysis. Shenoy (2010) proposed the unified conceptual approach to determine the minimum clean energy resource targets for energy allocation networks. The approach has also been extended to establish minimum resource targets for various process integration problems, such as the design or planning of heat/mass exchange, water, hydrogen, carbon emission and material reuse networks (Shenoy, 2011). After the initial identification of feasible targets via Pinch Analysis, subsequent cost analysis and optimization are then incorporated into the unified conceptual approach (Shenoy and Shenoy, 2012). Multi-objective Pinch Analysis is used to minimize energy and freshwater consumption for chemical processes (Jia et al., 2011). Regardless of the quality index used, these methodologies are unified by a set of key principles that are discussed in detail by Tan and Foo (2013).

In this work, the analysis is derived from pinch analysis techniques using composite curves, even though the actual implementation presented here does not utilize the pinch point itself. Nevertheless, this analysis retains some essential features from the family of pinch methods, i.e., visually-oriented display of data to facilitate insight-based decision making. This work focuses on the adjustment of the energy Source Composite Curve to meet the carbon intensity reduction target as the main quality metric. Other quality metrics are then taken into account as well. This strategy is analogous to the well-known *ε-constraint method* used for solving multiple-objective mathematical programming models (Haimes and Freeman, 1975), which uses a primary objective function to convert them into the equivalent single-objective formulation. For each metric, only the Source Composite Curve will be plotted instead of the complete energy planning Composite Curves (Tan and Foo, 2007). The first step of the targeting procedure is the rearrangement of the energy source data in the order of ascending footprint factor. As shown in Fig. 1, the Source Composite Curve for these sources is plotted on cumulative footprint vs. cumulative electricity output diagram. Each electricity source is plotted as a segment whose power output and absolute footprint correspond to the horizontal and vertical axes of the diagram, respectively. Consequently, the slope of each segment corresponds to its footprint factor, given in intensity units (such as kg CO_2-e/kWh). The coordinates of the endpoints of the Source Composite Curve gives total electricity output and total footprint.

Please cite this article in press as: Jia, X., et al., Multi-dimensional pinch analysis for sustainable power generation sector planning in China, Journal of Cleaner Production (2015), http://dx.doi.org/10.1016/j.jclepro.2015.10.102