Applied Energy xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Applied Energy

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

Embodied energy analysis for coal-based power generation system-highlighting the role of indirect energy cost

X.D. Wu [a], X.H. Xia [b,1], G.Q. Chen [a,*], X.F. Wu [a], B. Chen [a]

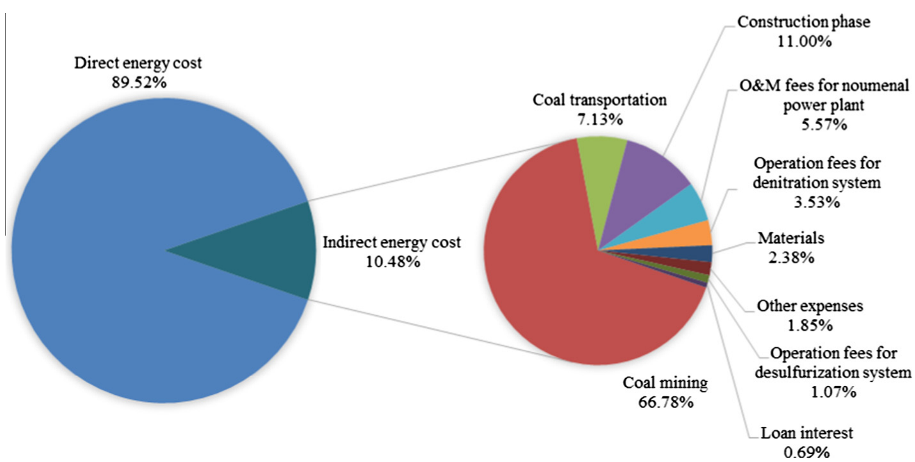
[a] College of Engineering, Peking University, Beijing 100871, China
[b] School of Economics, Renmin University of China, Beijing 100872, China

HIGHLIGHTS

- An embodied energy accounting for a typical coal-fired power system is undertaken.
- An inventory of life cycle energy inputs for the power plant is established.
- Full consideration is given to energy embodied in materials, equipment and services.
- The indirect energy cost shares around one-tenth of the total.
- This work could be a reference for holistic evaluation of power systems worldwide.

GRAPHICAL ABSTRACT

The indirect energy cost shares around one-tenth of the total energy expenditure throughout the typical power plant's lifetime.



ARTICLE INFO

Article history:
Received 27 November 2015
Received in revised form 4 March 2016
Accepted 5 March 2016
Available online xxxx

Keywords:
Coal-based power generation
Embodied energy accounting
Benchmark
Indirect energy cost

ABSTRACT

Coal-based power generation accounts for over two fifths of global electricity supply and is supposed to be continuing its leading role in the coming decades. However, an integrated embodied energy accounting for typical coal-fired power system seems to be in its vacancy. To help erect a benchmark for energy analysis of electricity production, this study has for the first time established a complete inventory of energy inputs in the life cycle of a typical coal-fired power plant. Distinguished from previous works, with the support of ecological input–output database, this paper gives full consideration to the energy embodied in materials, equipment and services that have been traditionally neglected. The indirect energy cost is illustrated to be a non-negligible component, sharing around one-tenth of the total. This work could be a reference example for holistic energy evaluation of power generation systems worldwide. In current context of energy conservation and emissions abatement, it is of significant importance as the retrofitting of power generation systems may initiate large amounts of indirect energy cost. Besides, by calculating the nonrenewability indicator for the typical coal-fired power system, the energy saving potentials of several renewable alternatives are enunciated in this work. It may provide essential implications for policy makers in renewable deployment.

* Corresponding author.
E-mail address: gqchen@pku.edu.cn (G.Q. Chen).
[1] X.H. Xia contributed equally as the 1st author.

http://dx.doi.org/10.1016/j.apenergy.2016.03.027
0306-2619/

Please cite this article in press as: Wu XD et al. Embodied energy analysis for coal-based power generation system-highlighting the role of indirect energy cost. Appl Energy (2016), http://dx.doi.org/10.1016/j.apenergy.2016.03.027

1. Introduction

1.1. Status of thermal power worldwide and in China

Energy shortage is acknowledged as a worldwide concern in a globalized economy fueled by fossil resources. According to British Petroleum (BP), in 2013 the world's primary energy consumption escalated to 12928.4 million tonnes oil equivalent, nearly 1.6 times compared with that in 1993 [1]. Around a half of the global primary energy use is by the power generation systems for electricity supply [2]. In 2013, as stated by International Energy Agency (IEA), the gross electricity production has reached 23,391 TW h, which reports a 2.9% increase than 22,740 TW h in 2012 [3]. Appreciated for the abundance, stability and price advantages, coal plays a salient part in electricity delivery, which has taken up around 40% of global electricity generation for decades [4]. The world's total installed capacity for electricity generation has risen to 5550 GW in 2012, among which fossil fuel-based (mainly coal-based) power generation systems reach an installed capacity of 3606 GW [5]. Without technical breakthrough for new energy alternatives, coal is expected to retain an irreplaceable place in electricity generation worldwide.

China, as the world's largest developing country, has for years been the world's biggest growth market for energy demand. Serving the pivotal role for electricity delivery, power sector requires a vast usage of fossil resources to sustain the robust economy. By the end of 2012, China has become the largest electricity producer all over the world, sharing around 22% of the global electricity production [5]. Characterized by the status quo of fossil resources (rich coal, meager oil, scarce gas) in China, coal-fired power plant has for decades been in a dominating position for domestic electricity delivery. By the end of 2013, the total installed capacity in China has reached 1257 GW and 68% of them is based on coal [6]. According to National Bureau of Statistics, the electricity production in 2012 reaches a total amount of 4988 TW h, about 78% of which is supplied by coal-fired power plants [7]. Due to the rising concern in fossil resources depletion and environmental pollution, a number of initiatives are proposed by the government to propel sustainable development. Renewable alternatives, such as photovoltaic, concentrating solar power, wind power, hydropower and nuclear power are widely raised [8–10]. In the *Twelfth Five-Year Plan*, a targeted goal is established to respectively increase the installed capacity of renewable energy to 160 GW and the proportion of renewable energy generation to 20% in the power mix by 2015 [11]. With the government support, renewable energy has been warmly embraced in these several years [12,13]. However, held back by the technical immaturity, high cost as well as the difficulty in grid connection, renewable energy is unlikely to replace thermal power generation for electricity supply in the short to middle term. In the forthcoming decades, thermal power is supposed to maintain its salient role in electricity generation. It is estimated that an additional capacity of 1260 GW, 70% of which is coal-fired power plants, is supposed to be installed in China by 2030 [14].

1.2. A review of energy evaluation studies for coal-based generation system

Given the dominant share of thermal power in the power sector, it remains a critical task to figure out the energy cost of coal-based generation system, which has aroused numerous attention in the academic field. The total energy cost of a thermal power generation system could be categorized into two groups, direct energy cost associated with fuel input, and indirect energy cost embodied in fuel production, fuel transportation, materials, equipment and services. For the direct energy usage, it has gained wide attention in industrial works due to its significant energy content. With regard to the indirect energy expenditure, it is related with the energy cost in the processes including construction, fuel preparation and transportation, materials and equipment manufacturing, plant decommission. Traditionally, in a number of studies, the energy expenditure of coal-fired power generation systems is generally treated as the energy contained in the fuel, based on which the energy efficiency could then be acquired [15,16]. For optimization of coal-fired systems, some works have investigated the possibility of increasing power generation efficiency [17,18]. For instance, by using differential evolution Wang et al. [19] explored multi-objective optimization of coal-fired power plants. The results suggest a 2% increase of the optimal efficiency. Whereas, it shall be also noted that, the energy expenditure in upstream, operational and downstream processes, including coal mining, transportation, plant construction and decommission, is not taken into consideration. Therefore, though the power generation efficiency within the power plant is to an extent enhanced, the incremental indirect energy expenditure caused by the retrofitting of coal-fired power systems (such as equipping of new facilities) may neutralize the efficiency improvement. To fairly assess the overall performance of coal-based power plants, a holistic manner is essential.

Fully recognizing that, some researchers began to investigate the energy performance of coal-fired plants in different countries in a cradle to grave manner [20]. Life cycle energy analysis as process analysis is widely applied in the associated works. All the energy inputs to the electricity production are incorporated, not only the direct energy inputs, but also the energy required to produce the fuel, materials, equipment, services that are supplied for power generation in all the stages. Appreciated for the merits, this method has been widely applied for decades.

In 1999, sponsored by the government, Spath et al. [21] led a NREL (National Renewable Energy Laboratory) report to examine the energy cost and CO_2 emissions of a typical US coal-fired power plant in a LCA (life cycle assessment) manner. The net energy ratio of the coal-fired power plant, which is defined as the total energy output divided by the summation of all the direct and indirect energy inputs, is calculated as 0.29. Different stages including equipment manufacturing, coal mining, transportation, chemicals production, power generation and waste disposal are all included to draw a complete picture of the energy flows. Founding on the process analysis, White and Kulcinski [22] undertook a birth to death analysis for the energy payback ratio of coal power plants in US, which is defined as the total useful energy produced by the power plant divided by the total energy invested. The selected 1000 MW coal-fired plant turns out to be with an energy payback ratio of 11%.

In recent years, a surging wave of interest has rushed towards energy assessment for carbon capture power plants, in which traditional thermal power plants are taken as reference for comparison [23,24]. By applying a techno-economic model, the life cycle efficiencies of the 500 MW pulverized coal-fired plant in UK equipped with and without CCS facilities are both examined in the study performed by Odeh and Cockerill [25]. The life cycle efficiency for the super-critical power plant proves to be 39.5%. Meanwhile, an evident drop of the efficiency could be seen after the plant is equipped with carbon capture facilities. In Pehnt and Henkel's work [26], the lifetime cumulative energy demand of power plant with post-combustion carbon capture facilities is estimated and compared with that of traditional pulverized coal-fired power plant. The result suggests that the fuel related energy cost accounts for over 99% of the cumulative energy inputs. Besides,