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A life-cycle comparison of the energy, environmental and economic impacts of coal versus wood pellets for generating heat in China

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ABSTRACT

In this study, we investigated whether wood pellets were more sustainable than coal for heating buildings in China by presenting a "fuel-to-heat" energy, environmental and economic comparison for both energy sources. Pellet and coal heating systems were modeled using a process-based life cycle inventory modeling approach, and the energy consumption and air pollutant emissions were calculated in Gigajoules (GJ). Wood pellets were also analyzed for their costs and market competitiveness against coal and other fossil fuel heating alternatives. The results showed that the energy saving potential from using pellets instead of coal was 1382 MJ for every 1-GJ of heat generated. Greenhouse gas emissions from pellets were 11.76 kg CO_2-eq GJ^{-1} heat, which were approximately 94% less than emissions from coal heating systems. Also, the wood pellet systems reduced SO_2, NO_x and PM emissions by 86%, 56% and 33%. However, the cost of pellets is significantly higher than the cost for coal, and is the primary impediment for the transition from coal to pellets in China. In addition, multiple consumers of wood residue, unstable heat values of pellet, limited supplies, and the lack of product and heating equipment standards also render the transition from coal to pellets impractical.

1. Introduction

The rapid economic growth in China is heavily dependent on the consumption of coal, which dominates the country's primary energy supplies by approximately 66% as of 2013 [1]. The electrical, steel and heating industries account for approximately 80% of China's coal consumption [2], which is expected to rise with the booming economy [3]. Coal combustion is primarily responsible for China's air pollutant emissions of CO_2 (85%), SO_2 (90%) and NO_x (70%) [2,4]. The severe haze, consisting mostly of fine particulate matter ($PM_{2.5}$), in Northern China was reported to originate from coal combustion used for residential heating [5–7]. Therefore, China needs alternative energy sources to reduce environmental pollutions and to improve air quality. Some provincial governments in Northeast China, such as the Jinlin and Hebei Province, have even proposed regulations to ban coal-fired heat generation in urban areas.

Biomass energy is a promising alternative to such limited fossil fuel reserves in China as coal, oil and gas [8]. However, since biomasses are scattered resources with lower energy densities and are inconvenient to store and transport, for biomasses to be practical in large-scale applications, they must first be converted to a solid fuel by pulverizing, drying and compression, so that they are dry and dense with a high heat value [9–11].

In China, research in biomass compressing technology has been growing since the first rice husk-molding machine was tested by a food-processing factory in the Hunan Province in 1985. This technology is currently ready for industrial use [12]. Both agricultural and wood waste can be used to produce biomass solid fuels. The wood pellets produced by wood residue are favorable feedstock energy because of their high calorific value, low ash content and slagging rate. China's production of wood pellets in 2010 was 1.93 million tons, which was approximately 72% of the solid fuel supply [13]. The annual generation of wood waste in China is approximately 903 million tons, of which one third are applicable for energy production [14]. Despite the abundant supply of wood waste, the development and use of wood pellets is still in its infancy. But,

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Nomenclature

Abbreviations

CTH	coal-to-heat
EPBT	energy payback time
FCHG	fuel cost of heat generation
GHG	greenhouse gas
LCA	life cycle assessment
LCI	life cycle inventory
LHV	lower heating value
NPV	net present value
PP	payback period
PTH	pellet-to-heat
R&D	research and development
SI	Supplementary Information
TE	thermal efficiency

Symbols

β	cost-profit ratio of wood pellet fuel
EC_C	construction cost of pellet plant
EC_F	feedstock cost of pellet plant
EC_O	operation and maintenance cost of pellet plant
EC_{WP}	unit economic cost of pellet production
$FCHG_C$	fuel cost of heat generation from CTH system
$FCHG_{WP}$	fuel cost of heat generation from PTH system
L_C	LHV of coal
L_{WP}	LHV of wood pellet
P_C	price of coal
P_{WP}	expected market price of wood pellet
θ_c	TE of coal boilers
θ_{WP}	TE of pellet boilers

as the Chinese government implements stricter coal control policies, such as substituting bulk coal for heating buildings in the northern areas, wood pellets have the opportunity of large-scale development. In 2010, Europe used nearly 100% of wood pellet outputs for its heat generation [15,16].

To determine whether wood pellets are a green alternative for coal in China, a quantification and comparison of "fuel-to-heat" energy, environmental and economic impact of both wood pellets and coal should be conducted. Although pellet combustion is relatively cleaner than coal, the decision to transition from coal to wood pellets in China's heat generation sector should be made prudently only after a thorough investigation of the supply-chain, because the harvesting and transporting of wood residues and pellet production also produce adverse environmental emissions.

Life cycle assessment (LCA) is a holistic approach to assess the cradle-to-grave energy and environmental impact of a product or service [17–19]. The method is commonly used to evaluate wood pellet production in Europe [20–25], Canada [26,27], the U.S.A. [28] and Japan [29]. As reported in literature, pellets produced by diverse biomass resources, such as wood waste, energy forest and grape marc have positive environmental benefits when substituted for fossil fuel energies to generate electricity or heat [21,24,28]. The main contributors of adverse environmental impacts were biomass plantation, pellet production and long-distance pellet transportation, depending on the raw biomass resource options, the conversion technologies used and the location of pellet markets [20,26]. Hu et al. evaluated the economic, environmental and social impacts of heat generation of briquette fuel from corn straw in China, and found that the life-cycle greenhouse gas (GHG) emissions of the fuel utilization was approximately 1 kg CO_2-eq GJ^{-1} heat [11]. Our previous study found that the nonrenewable energy consumption of wood pellets in China was only 0.09 MJ MJ^{-1}, which indicated high renewability [30]. However, to our knowledge, no LCA study has focused on wood pellet production and its use for heat generation in China, which is essential for the exploration and formulation of China's coal substitution policies.

We conducted a comprehensive study to calculate the fuel-to-heat energy and the environmental and economic impacts of the "fuel-to-heat" system of wood pellets in China based on a real plant in Changchun City, and assessed the substitutability of substituting wood pellets for coal to generate heat. Our study shows the "fuel-to-heat" energy consumption, air pollutant emissions and economic costs of transitioning from coal to pellets that will help policy makers in China and researchers better understand the environmental footprints and costs of coal versus pellet heat generation systems. Our study also provides insight for the future direction of transition from fossil fuels to other alternative energy sources for heat generation.

2. Methods and data

2.1. System boundaries and functional units

A process-based life cycle inventory (LCI) modeling approach was adopted to estimate the "fuel-to-heat" energy, environmental and economic footprints of wood pellets and coal, as shown in Fig. 1. The "fuel-to-heat" system consisted of fuel production, transportation and fuel combustion for heat generation. Calculations for wood pellet production were based on a plant in Changchun city, China, with an annual wood pellet production capacity of 10,000 tons. The plant was assumed to have a lifespan of 15 years based on the design documents of the pellet plant. The energy and materials data of the wood pellet production process were collected by a local investigation and by an interview with the plant manager. The material composition and equipment weights were obtained by field measurements and by consulting the technicians. The data used to estimate coal production were primarily obtained from the Ecoinvent 2.2 Database [31], which provides fundamental data of coal production in China. Wood pellets and coal were combusted to generate heat for hotels in Changchun City, and the functional unit in this study was 1-GJ (Gigajoule) of effective heat. Details of each process of the modeling are shown in Fig. 1 and described below in Section 2.2.

2.2. Life-cycle inventory analysis

2.2.1. Fuel production

The production of wood pellets consisted of a lumbering process, feedstock transportation and energy conversion, while the production of coal included coal mining and washing. The energy consumption and environmental emissions of the coal mining and washing were estimated using the Ecoinvent 2.2 Database [31].

The wood residues used for the wood pellet production were the lumber wastes from a natural Larch forest, a common tree species found in the northeast area of China. As shown in Fig. 1, the lumbering process included four steps: felling the trees (cutting), skidding the trees to a landing area (skidding), processing the trees to logs and loading them to trucks (processing & loading), and