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RESEARCH ARTICLE

# Cost of non-renewable energy in production of wood pellets in China

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**Abstract** Assessing the extent to which all bio-fuels that are claimed to be renewable are in fact renewable is essential because producing such renewable fuels itself requires some amount of non-renewable energy (NE) and materials. Using hybrid life cycle analysis (LCA)—from raw material collection to delivery of pellets to end users—the energy cost of wood pellet production in China was estimated at 1.35 J/J, of which only 0.09 J was derived from NE, indicating that only 0.09 J of NE is required to deliver 1 J of renewable energy into society and showing that the process is truly renewable. Most of the NE was consumed during the conversion process (46.21%) and delivery of pellets to end users (40.69%), during which electricity and diesel are the two major forms of NE used, respectively. Sensitivity analysis showed that the distance over which the pellets are transported affects the cost of NE significantly. Therefore the location of the terminal market and the site where wood resources are available are crucial to saving diesel.

**Keywords** wood pellet, non-renewable energy (NE), hybrid life cycle analysis (LCA), bio-fuel

## 1 Introduction

Wood pellets, a type of wood fuel, are generally made by compressing sawdust or pulverized woody materials. Because the raw materials are highly compressed, the pellets are extremely dense. They also have very low moisture content (below 10%). These two characteristics — high density and low moisture — ensure that the pellets have very high combustion efficiency (Uasuf and Becker, 2011). In Europe, wood residues have been converted into pellets for heating homes since the 1970s (Magelli et al., 2009), although biomass-based solid fuels have not been as popular as biomass-based liquid fuels like ethanol as the latter can directly replace petroleum products. In China, interest in research on biomass compacting has been growing since the 1980s (Zhang et al., 2011). The first biomass-molding machine in China used rice husk and was tested by a food processing factory in Hunan Province in 1985. However, the technology turned out to be not only inefficient but also highly energy intensive, which hindered its commercialization until 2000. The technology has gradually improved thereafter; by 2009, about 60 pellet plants or demonstration sites had been constructed in China with a total annual output of 0.7 million tons of fuel. According to the national *Long- and Medium-term Plan on Renewable Energy*, consumption of pellets was expected to reach 1 million tons in 2010 and 50 million tons in 2020.

Different approaches, based on energetic or exergetic methods, have been proposed to assess the renewability of energy conversion systems, especially those related to renewable energy (Hu et al., 2004; Leng et al., 2008; Nguyen and Gheewala, 2008; Yang et al., 2009; Yang and Chen, 2012). One such indicator or measure of 'non-renewable energy (NE) investment in energy delivered', or non-renewable energy investment in energy delivered (NEIED), was emphasized by Chen et al., who used it to assess the renewability of solar power (a tower-type plant), wind power, and bio-ethanol (Chen et al., 2011a, 2011b; Yang and Chen, 2012), and found that the net energy value of what is claimed to be renewable bio-fuel before was not always positive (Yang and Chen, 2012).

Assessing the energy efficiency and environmental impact of biomass densification technology is now receiving increasing attention from researchers (Magelli et al., 2009; Fantozzi and Buratti, 2010; Lu and Zhang,

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2010; Pa et al., 2011; Sjølie and Solberg, 2011; Uasuf and Becker, 2011; Win et al., 2012). The energy return ratio (the ratio of renewable energy produced to nonrenewable energy) have generally been high (2.56–3.25) and the environmental performance has been good irrespective of the raw material and the accounting boundary (Magelli et al., 2009; Fantozzi and Buratti, 2010; Sjølie and Solberg, 2011). As mentioned earlier, biomass briquettes as fuel is a relatively new approach to biomass transformation in China, and has been studied only to a limited extent, mainly with respect to the technology research (Sheng and Wu, 2004; Ma and Zhang, 2006; Liu et al., 2011; Ouyang et al., 2011). Nevertheless, Lin et al. (2009) and Zhu et al. (2010) attempted life cycle assessment (LCA) of corn straw pellets in China with a process-based method. The results were different depending on whether energy input during the growth process of corn had been taken into account. So far, no research on LCA of wood pellets in China has been published in a journal, although such assessment is essential for further development of the technology. As mentioned in many studies, truncation error is inherent to varying degrees in the calculations related to LCA because, given the complex interdependencies among industrial sectors within the national economy, it is impossible to trace all direct and indirect inputs (Suh et al., 2004; Carpentieri et al., 2005; Hendrickson et al., 2006; Zhai and Williams, 2010). A hybrid LCA method has been developed to reduce truncation error by combining process-based LCA and economic input-output LCA (EIO-LCA) and it was adopted in evaluating bio-fuels and other forms of energy (Zhai and Williams, 2010; Wang et al., 2012; Zhang et al., 2012). Economic input-output LCA is an extension of EIO analysis to the physical realm, which has been developed in the US by researchers at Carnegie Mellon University (CMU) (Lave et al., 1995).

The present study sought to evaluate the cost of NE in the production of wood pellets in China with the hybrid LCA approach. Since detailed data on pellet production in China were not available, a typical pellet plant was chosen for a case study. The plant, in Huinan County of Jinlin Province, produced 8,000 t of pellets annually. The study took into account the flows of non-renewable material and energy throughout the life cycle, right from collection of raw material up to the delivery of pellets to the homes of end users (Fig. 1). The indicator of NEIED was devised to reveal the extent of NE cost of wood pellets (Chen et al., 2011a). In addition, the two other studies on corn straw pellets mentioned earlier were used for comparison.

## 2 Methodologies

### 2.1 Hybrid life cycle analysis model

The bottom-up approach (represented by process analysis) and the top-down approach (represented by input-output analysis) are two independent quantitative approaches used for calculating the embodied energy of a product or service (Bullard et al., 1978; Hondo et al., 2002). The accuracy of process analysis entirely depends on tracing all the stages of the production process. However, some inputs have to be ignored or truncated after a few stages because the time-consuming of process is to the extent of being infinite, and some steps even lead back to the beginning. Input-output analysis was developed by Wassily Leontief to quantify the relationships between different sectors of an economic system by considering monetary transactions among the sectors (Baral and Bakshi, 2010). An input-output table can thus build a complete model of the economy, but it lacks detail because the table can only be an aggregation of hundreds of sectors in an economy, and the results can only give the average energy intensity of a sector's output (Hondo et al., 2002).

After considering the pros and cons of the process and input-output analyses, Bullard et al. (1978) suggested using a hybrid method to determine the energy required to

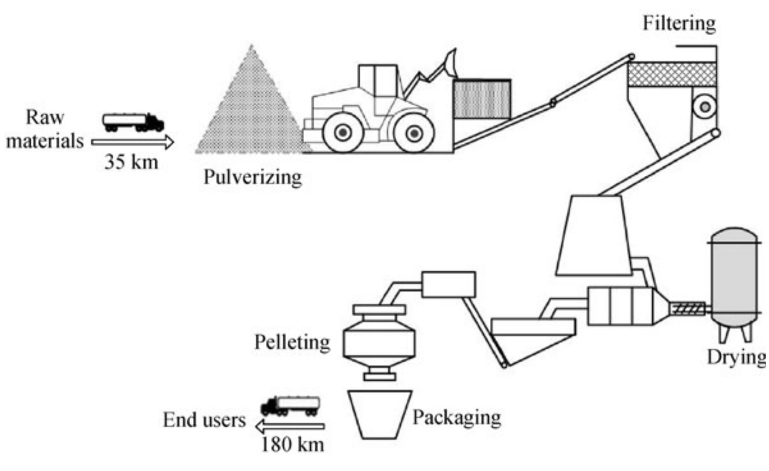


**Fig. 1** The flows of wood pellet's production

manufacture a target product to increase the completeness of the system boundary and to reduce uncertainty. This study used an additive hybrid method to calculate the NE cost of wood pellet production based on a few fundamental equations: process-based LCA was used to quantify the direct energy input at each stage and EIO-LCA was used to trace all the indirect energy use embodied in the materials and services necessary for raw material collection, conversion process, and delivery of pellets to end users.

$$E_{\text{total}} = E_{\text{p}} + E_{\text{EIO}}, \tag{1}$$

$$NE_{\text{total}} = NE_{\text{p}} + NE_{\text{EIO}}, \tag{2}$$

where $E_{\text{total}}$ and $NE_{\text{total}}$ are the total energy and NE invested in the whole production and transport processes, respectively; $E_{\text{p}}$ and $NE_{\text{p}}$ are the direct energy and NE inputs, respectively, calculated by process-based LCA and expressed as a sum of the product of fuel combustion and their lower heating values (LHVs); and $E_{\text{EIO}}$ and $NE_{\text{EIO}}$ are the indirect energy and NE inputs calculated by EIO-LCA, i.e., multiplying the cost price of material or labor by the energy or nonrenewable energy intensity of the relevant sector that is associated with the inputs. The EIO-LCA model based on the 135-sector input-output table of China is adopted in this study, the construction and earlier adoption of which can be found in our previous work (Wang et al., 2012; Zhang et al., 2012).

### 2.2 System boundary and data description

As mentioned above, the typical wood pellet plant located in Jinlin Province forms the basis for our analysis. The whole production process, as shown in Fig. 2, consists of raw material collection, the conversion process (including sub-processes like pulverizing, filtering, drying, pelleting and packaging as shown in Fig. 1) as well as the delivery of pellets to end users. The direct energy inputs computed by process-based LCA include diesel consumption for transport, raw material inputs (biomass in the form of woody materials, sawdust, and rice husks), and electricity consumption during the conversion process (Fig. 2). The hidden and indirect energy cost of devices and labor during their manufacturing or providing process were calculated by EIO-LCA. Similarly, the cost of indirect fossil energy used for generating the directly used energy is also calculated by the EIO-LCA. It was assumed that no extra energy is used in the combustion of pellet (Lin et al., 2009).

All the data used in this study were derived from design documentation and local investigation of the chosen pellet-

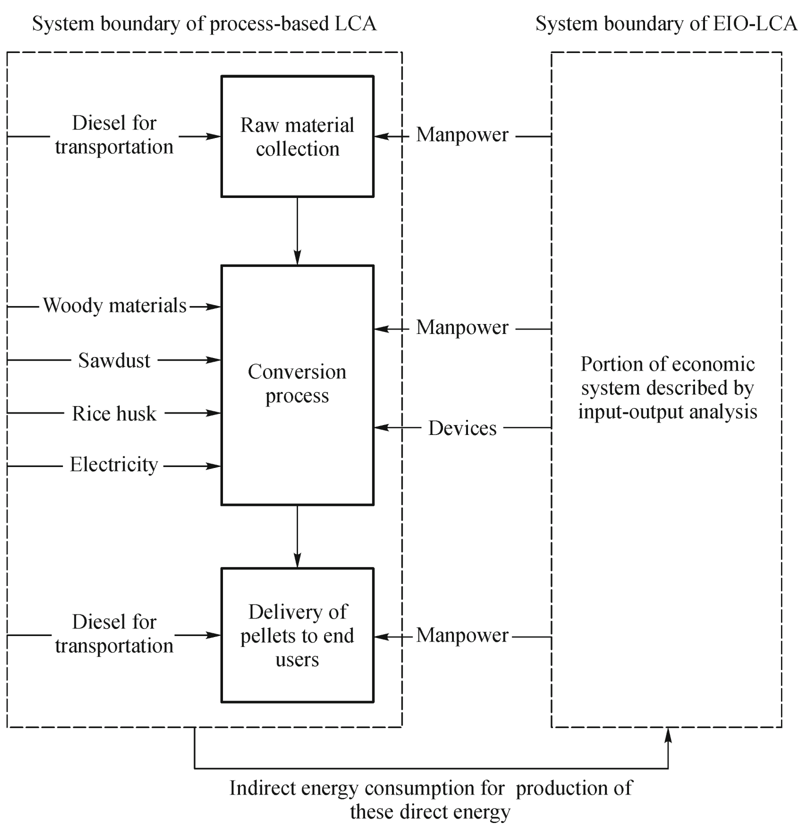


**Fig. 2** Definition of the direct and indirect energy inputs

production plant. The woody materials are gathered from a forest farm 35 km from the plant on average. The cost of diesel consumed for transporting the raw material to the plant was estimated at 0.05 L/(t·km) (Chen et al., 2011a). The pulverized woody material is mixed with sawdust and rice husk, both transported from a distance of about 5 km, to improve the adhesion and hardness of the pellets. After pelleting and packaging, the pellets are transported over 180 km to Changchun, the capital of Jilin Province, for delivery to end users. Apart from the cost occurred during transportation process of raw materials and the final pellets, diesel is also combusted for transport within the plant, amounting to 0.87 L to produce 1 t of pellet. It is assumed that the electricity used in this plant is NE since the power grid in north China is mainly supported by coal-based electricity. The other data on the inputs required to produce 1 t of pellets are given in Table 1. The hybrid LCA base year is 2007, and the cost data used for EIO-LCA are all producer prices adjusted to 2007 (producer data are obtained by deducting the profit and taxes from the market price). It is worthwhile to note that the designed life cycle of the plant is 15 years; therefore, the device inputs are assigned evenly to each ton of product. The dismantling and disposal of the plant is unpredictable, and it is assumed that no device can be recycled at the end of the life of the plant.

**Table 1** Components of LCA of wood pellet production (to produce 1 t of pellets)

| Component | Quantity | Per unit/CNY | Total/CNY |
|---|---|---|---|
| Woody materials | 0.49 t | 250.00 | 121.33 |
| Sawdust | 0.14 t | 360.00 | 49.92 |
| Rice husk | 0.69 t | 320.00 | 221.85 |
| Electricity | 54.85 kW·h | 0.75 | 41.13 |
| Device | | | 18.23 |
| Labor | | | 76.84 |
| Diesel for transport | 10.93 L | 7.35 | 80.33 |

## 3 Results and discussion

### 3.1 Non-renewable energy cost

Raw material is a large input in any bio-energy project. Including biomass materials, the total energy investment ($E_{total}$) in the whole production process amounted to 2.25E + 04 MJ for 1 t of wood pellets. Given that the LHV of wood pellets is 16.73 MJ/kg as measured by technicians of the plant, the energy cost ratio of wood pellet was 1.35. In addition, the NE cost ratio was 0.09, indicating that only 0.09 J of fossil energy is needed to generate one unit of wood pellets, which shows that the process is high on renewability. Dividing total NE consumption over the whole life cycle by annual energy delivered, the energy payback time (EPBT) was 1.32 years.

The NE costs of each stage from the perspective of whole production process are shown in Table 2.

As shown in Table 2, directly used NE was only 5.88E + 02 MJ/t, accounting for about 40% of the cost of NE; the balance was accounted for by indirect use. The conversion process (from pulverizing to packaging) and delivery of pellets to end users were the two largest stages in terms of energy consumption, accounting for 46.21% and 40.69% of the totals, respectively. Within the conversion process, drying the pulverized materials was the most energy-intensive component, which claimed 37% of the total cost of NE for conversion stage. Figure 3 shows the different sources of NE at each stage of the whole production process. Diesel consumed in transporting raw material to the plant and in transporting pellets to end users as well as that consumed in transport within the plant was the largest source of the total cost of NE, accounting for as much as 48%. In addition, the entire conversion process from pulverizing the material (biomass) to packaging the pellets — especially drying — is powered by electricity, which accounts for about a third of the total cost of NE incurred during the whole life cycle of pellet production.

### 3.2 Comparison with related studies

As mentioned earlier, two other studies (Lin et al., 2009; Zhu et al., 2010) on pellets, from corn straw, were chosen for comparison with the results of the present study. It is worthwhile to note that only electricity and oil were taken into account in calculating the cost of NE in producing pellets from corn straw, equivalent to the direct NE cost in the present study. As shown in Table 3, the difference between the results of the earlier studies is mainly from the raw material collection stage, because some indirect costs at this stage, namely the inputs for growing the corn, have been considered as part of the total costs of producing pellets from corn straw in research of Zhu et al. (2010). Producing pellets consumed less electricity during the pelletization process of the present study because more than half the quantity of raw materials comprised sawdust and rice husk — sources that required no pulverization. On the other hand, more oil was consumed in the present study because of the greater distances involved, both in transporting raw materials to the pelleting plant and in delivering pellets to end users. The NE costs reported in the two earlier studies are 20%–40% less than ours, which is probably attributed to the ignorance of indirect energy use in previous studies.

### 3.3 Sensitivity analysis

Given the three stages that accounted for most of the NE consumed during the chain from raw materials to delivery

**Table 2** Cost (MJ/t) of NE in each stage of production of wood pellets

| Components | Direct NE | Indirect NE | Subtotals | Percentage/% |
|---|---|---|---|---|
| Raw material collection | 3.78E + 01 | 1.56E + 02 | 1.93E + 02 | 13.10 |
| Pulverizing | 4.17E + 01 | 8.80E + 01 | 1.30E + 02 | 8.79 |
| Filtering | 4.54E + 01 | 5.71E + 01 | 1.02E + 02 | 6.94 |
| Drying | 9.06E + 01 | 1.54E + 02 | 2.45E + 02 | 16.60 |
| Pelleting | 1.47E + 01 | 9.16E + 01 | 1.06E + 02 | 7.20 |
| Packaging | 3.60E + 01 | 6.27E + 01 | 9.86E + 01 | 6.68 |
| Delivery to end users | 3.22E + 02 | 2.79E + 02 | 6.01E + 02 | 40.69 |
| Total | 5.88E + 02 | 8.88E + 02 | 1.48E + 03 | 100 |

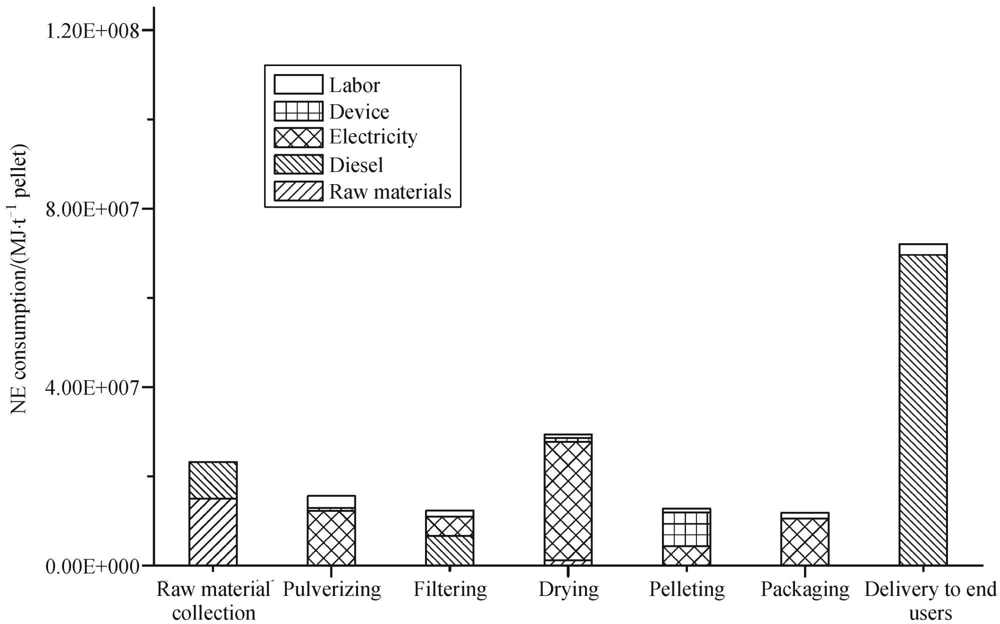


**Fig. 3** Share of different sources of NE at each stage of production of wood pellets

**Table 3** Comparison of the costs of NE in the present study with those in two earlier studies

| Component or stage | Lin et al. (2009) | Zhu et al. (2010) | Our study | |
|---|---|---|---|---|
| | | | Direct | Indirect |
| Collection of raw material (J/J) | 3.76E − 05 | 1.25E − 03 | 2.26E − 03 | 9.30E − 03 |
| Pelletization (J/J) | 4.67E − 02 | 6.50E − 02 | 1.37E − 02 | 2.71E − 02 |
| Delivery to end users (J/J) | 1.80E − 03 | 2.02E − 03 | 1.92E − 02 | 1.67E − 02 |
| Self-energy of 1 t of pellets (MJ) | 1.67E + 04 | 1.68E + 04 | 1.67E + 04 | 1.67E + 04 |
| NE cost (J/J) | 4.85E − 02 | 6.83E − 02 | 3.51E − 02 | 5.31E − 02 |

Note: The earlier study considered the costs of producing pellets from corn straw.

of pellets to end users, three factors, namely the distance over which the pellets are transported for delivery to end users, electricity consumption, and the price of raw materials, were selected to conduct a sensitivity analysis of their influence on the cost of NE (Fig. 4). The transportation distance affects the cost significantly: if the distance between the plant and the end users is halved, the costs fall by nearly 20%. Therefore, avoiding long-distance transport by relocating the sources of raw material and the terminal market may be an efficient way to reduce

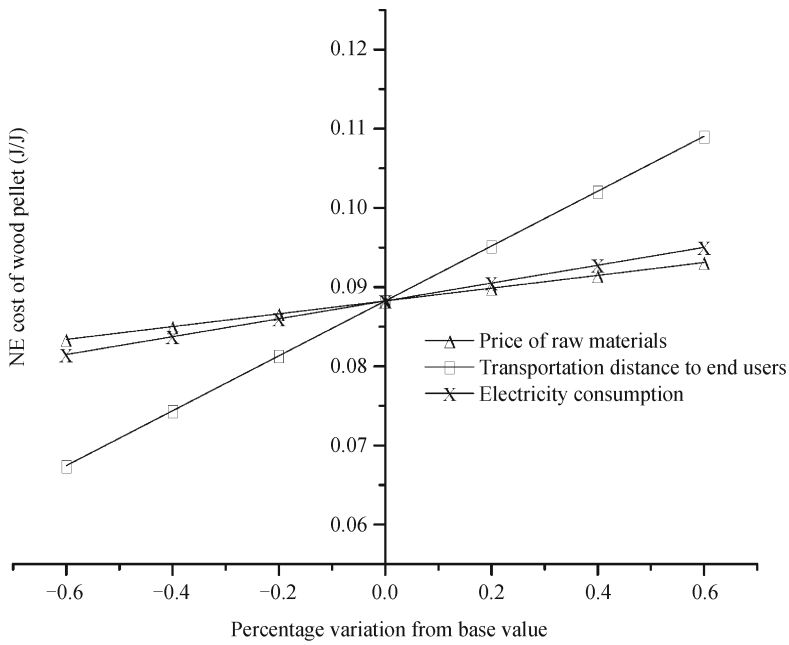


**Fig. 4** Sensitivity analysis: the cost of NE consumed in producing wood pellets

energy consumption during the life cycle of wood pellets. In addition, technological innovation to reduce electricity consumption during the conversion process is also essential to reduce the total cost of NE.

## 4 Conclusions

In China, renewable sources of energy are expected to contribute greatly to ensuring energy security and to mitigating the adverse effects of climate change. However, it is important to estimate the cost of NE incurred in generating energy from what are claimed to be renewable sources of energy because differing amounts of fossil-based, or non-renewable, energy are consumed in producing such renewable sources in the first place. For a typical wood pellet plant in China, the NE to produce 1 J of pellets was as low as 0.09 J, showing that converting waste biomass into pellets in this case was a process high in renewability. The energy payback time of the pelletizing plant was calculated to be 1.32 years. The research also showed that the diesel combusted in delivery of pellets to the end users and the electricity used in the conversion process are the main contributors to the total cost of NE. The costs as estimated in the present case study are 20%–40% higher than those estimated in earlier studies, which is probably attributed to the consideration of indirect energy inputs usually ignored in process-based LCA because of limited data.

In China, pelletized wood residues may be a promising substitute for fossil energy in the future according to the results of our study. However, it is essential to set up such plants at the right locations that minimize the distances over which both the raw materials for pellets and the finished goods (pellets) have to be transported; otherwise, the high energy intensity of transport and scarcity of raw materials may impede further development of this potential source of renewable energy.

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