J Wood Sci (2016) 62:93–100
DOI 10.1007/s10086-015-1515-6

ORIGINAL ARTICLE

Analysis of effect on CO_2 emission reduction and cost estimation for the use of Bio-coke: a case study of Osaka, Japan

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Received: 23 June 2015 / Accepted: 4 September 2015 / Published online: 5 October 2015

Abstract Bio-coke (BIC) is drawing attention as a coal-coke substitute in industry. Though BIC can be used as a carbon-neutral fuel, its overall benefits, including the environmental impacts associated with its production processes and its merits as an alternative fuel, remain unknown. In this study, we investigate the overall impacts and benefits related to BIC production processes and alternative fuel applications by looking into the case of Takatsuki in Osaka Prefecture, the only commercial BIC plant in Japan. Based on the system boundary set, we calculated CO_2 emissions per ton of BIC associated with its manufacturing and transportation processes to be 1.01 t CO_2. CO_2 emission from electricity consumed in the process was found to be the largest, accounting for 74.7 % of total emission. The analyses also revealed that using one ton of BIC as alternative fuel in industry instead of coal-coke could result in avoiding 2.16 tons of CO_2 emissions, showing a clear environmental benefit. While BIC's calorific value is almost same as pellet's, BIC had higher gross margin and energy density than pellet produced in the same facility. These findings enhance the merits of producing BIC from wood biomass and could lead the way to revitalizing forestry in Japan.

Keywords Bio-coke · CO_2 emission · Alternative fuel · Net energy balance · Local forestry

Introduction

In Japan, forestry dilapidation and the weakening of regional economies caused by the decline of forestry have hindered the utilization of forest biomass. To use natural resources sustainably, we must consider not only environmental aspects, but also economic effects on local inhabitants and the significance of using techniques already in practice in the area. In the meantime, there are global-scale environmental issues such as the depletion of fossil fuel and global warming. Using energy derived from local forest biomass is now attracting attention as one of the ways to address the pressing issue [1, 2]. Environmental conservation, economic activity, and area fixity are all important to the sustainability of forestry [3]. Environmental conservation through the use of local resources can become the key in accomplishing all three aspects. For example, biomass fuels such as wood pellets are considered to be a carbon-neutral energy resource. In addition, because the pellets are locally produced and consumed, local profit can be created [4].

In the late 2000s, Bio-coke (BIC) was developed by Kinki University (domestic patent no. 4089933) in Japan [5]. Since it has a high energy density, it can be used as a coal-coke substitute in large-scale industrial processes [6, 7]. The characteristics of BIC can be summarized as follows [6, 8]: (1) no raw materials are lost in the process of making BIC; (2) 100 % of the energy in the raw materials is retained; (3) BIC has a high energy density, so its transport efficiency is higher than that of wood pellets, (4) BIC is a solid fuel suitable for storage and transport, and

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(5) stable combustion is possible at high temperatures, making BIC a suitable alternative to fossil fuels. Further, BIC can utilize not only unused biomass and thinned wood, but also construction waste and food residue. In other words, it can be the basis for a cascade recycling system for industrial wood waste. In general, however, the costs of forest maintenance exceed the profit it generates. In fact, forestry operation cannot be maintained without relying on subsidy. This problem has hindered the thinning of forests and the promotion of utilizing unused wood. BIC production has the potential to solve this problem by not only utilizing unused wood biomass, but also by stimulating industrial demand.

As of 2014, there is only one commercial BIC plant in Japan, run by the Osaka prefectural forest owners association (OFOA). Its BIC production supplies one manufacturing company in Aichi Prefecture, where it is used as an alternative to coal-coke. One of the raw materials for making BIC is thinned wood from the OFOA's forest management activities. However, demand for BIC is still limited and BIC production at present does not necessarily promote the utilization of unused wood in the region. We posit that the not knowing the actual benefits of producing and using BIC hinders the dissemination of BIC technology. Though BIC is used as a carbon-neutral alternative to coal-coke, its overall benefits, including the environmental impacts associated with its production processes such as CO_2 emission, remain unknown. In fact, most previous research has focused only on the environmental aspects of using raw materials to make bio-energy products [9–12] and on BIC's physical and scientific characteristics as a fuel [13–15]. For example, Uchiyama et al. [16] estimated the CO_2 emission reduction attainable by using BIC as a substitute fuel. Their study, however, did not include the estimation of any discharge at the time of production. Few studies have considered the total CO_2 emissions (environmental impacts) of the entire process, from logging to consumption, and so BIC's actual net environmental benefits have not been clear.

In this study, we analyze the overall impacts and benefits of the OFOA's BIC production processes and of using BIC as an alternative fuel. Specifically, we (1) delve into environmental impacts (CO_2 emissions) associated with producing BIC and its energy balance; (2) compare the CO_2 emissions, net energy balance, usability, and costs between BIC and wood pellets productions, and (3) investigate the CO_2 emission reduction attainable using BIC as an alternative to coal-coke. The potential and significance of BIC production and use are elucidated by these analyses and the findings will shed light on the merits of producing BIC from wood biomass. The information and implication derived from the results could lead the way to revitalizing forestry in Japan.

Method

Study sites

The head office of the OFOA and one of its branches, the Mishima office, are located in Takatsuki city, north of Osaka (Fig. 1). Osaka Prefecture is 31 % forest, making it the least forested of all of Japan's prefectures [17], but Takatsuki city has the third highest percentage of forest (44 %) in Osaka Prefecture [18]. BIC is made at a plant in the OFOA factory north of Takatsuki city. Wood chips, pellets, and compost are also made in these facilities. There are two plants in the factory. One is for BIC and the other is for pellets. The quantities of electricity and fuel used are periodically measured in each facility. Chips and compost are made outside. The raw materials for the biomass fuels are thinned wood produced by the OFOA's forest management activities and wood from forest development sites including the construction of the Shin-meishin highway in Osaka Prefecture started in 2009.

Analysis of CO_2 emission and energy balance

Since the overall merit of Bio-coke utilization as carbon-neutral energy source is best judged from the evaluation of CO_2 emission, we aim to estimate CO_2 emission as the proxy of greenhouse gas associated with producing Bio-coke. One ton of BIC produced is the functional unit, and the system boundaries of the evaluation stretch from raising the raw material to consumption by combustion (Fig. 2). The processes of discharging combustion ash and handling coolant, and emissions from workers' commutes are outside the system boundary of analysis. We obtained data where possible from the OFOA in interviews or in the form of data sets. Note that we calculated CO_2 emissions using the build-up method. Data that were difficult to acquire or measure were set based on previous research. As our main target is the processes involved in BIC production, other factors such as construction or maintenance of facilities and machines are not included in the evaluation. Energy inputs include fuels such as light oil, kerosene, gasoline, LP gas, mixed oil and multi-diesel oil, as well as electricity, all of which are used for the operation of BIC production in the case study site. The CO_2 emission factors for fuels and electricity used in this study are shown in Table 1 [19, 20]. We based our work on the data for a 2-year period from June 2012 to May 2014. No pellets or BIC were produced for several months. Even when no production is occurring, the production process is promoted along the way. Thus, we based our analyses on a 2-year average, not omitting data for the months when no fuel was produced. We also calculated the net energy balance

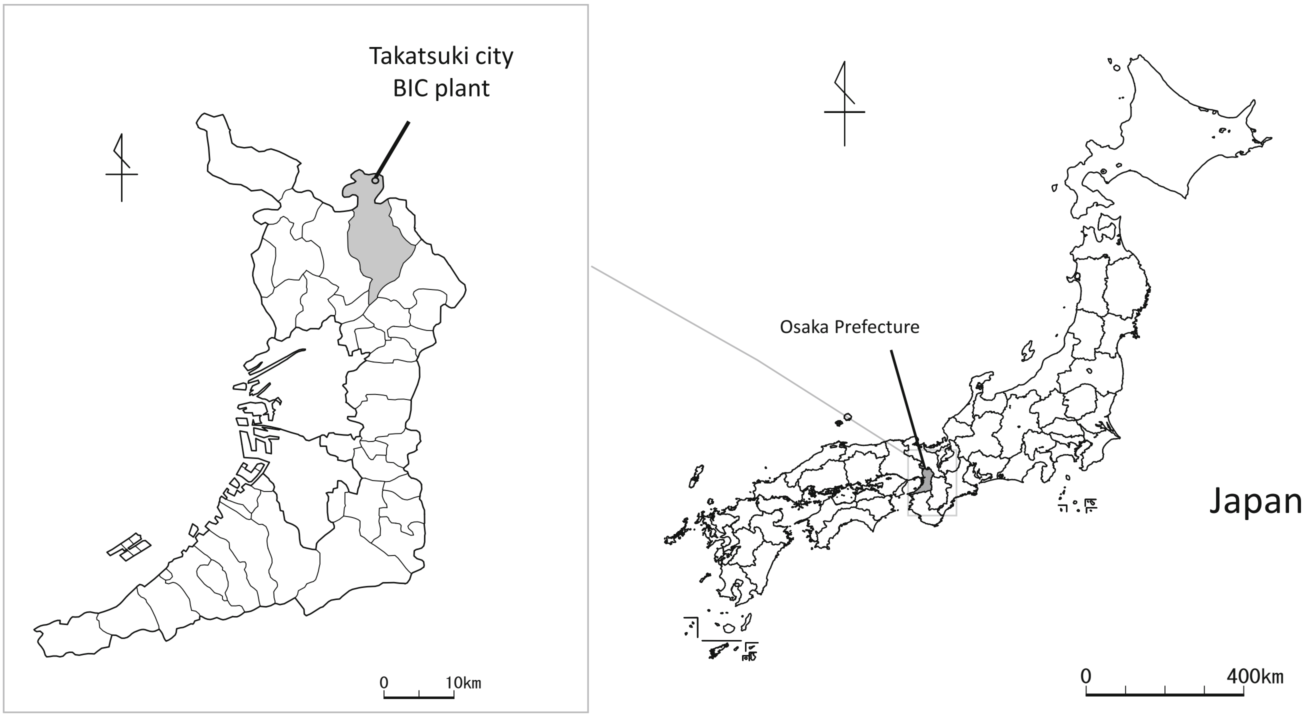

Fig. 1 Location of Bio-coke (BIC) plant. The map was drawn by authors using Mandara

(NEB). The NEB is used to compare amounts of biofuel energy and fossil fuel energy inputs. It is the ratio of energy output to energy input [21, 22]. Various fuels' calorific values per unit are shown in Table 2 [23, 24].

We used values from previous research data for the energy input required to obtain raw materials (processes I and II in Fig. 2). Specifically, we used the value of 17.5 kg CO_2 as the average CO_2 emitted in producing 1 m^3 of thinned wood [25]. Hitoe et al. [26] examined the CO_2 emission from silviculture through log production, showing that most of the environmental load was due to harvesting work, and that silviculture accounts for only 2 % of the total environmental load. Therefore, the environmental load from silviculture was not included in this analysis. According to the MAFF [27], 1 m^3 of wood used as a material input can produce 2.7 m^3 of chips on the stock volume basis. We used the value of 0.08 kg CO_2/km•m^3 for the CO_2 emitted by process II [25]. Along with thinned wood provided by the OFOA, most of the raw material comes from the construction site of the Shin-meishin highway, which on average is about 10 km away from the BIC plant. Because the sites where the OFOA thins the forest are also within the same area, a transport distance of 20 km round trip was used in process II.

For the manufacturing steps (processes III–X), we collected energy consumption data from June 2012 to May 2014 from the OFOA factory. We calculated the weighted average of the 26 months on a per unit production basis. Processing (1) includes producing chips used as raw materials for pellet and BIC production and chips used directly for combustion or gardening. Therefore, we included the LP gas used in office operations in Processing (1). Also, interviews at OFOA revealed that producing 1 ton of pellets requires 8 m^3 of chips and 1 ton of BIC requires 8.33 m^3 of chips. In Processing (2), 0.2 tons of pellets, produced at the plant, are used as fuel to produce 1 ton of BIC. In the sales and distribution process (process XI), BIC is transported to Toyota city in Aichi Prefecture. The transport distance was estimated to be 186.1 km, using the range-finding website "Map Fan Web" [28]. We assume that this is a one-way trip because the company loads the truck in the return path to Osaka. We found that a 10-ton truck is used for the transport, and the average load is about 9.5 tons. According to a previous study, the fuel consumption of a 10-ton truck is 2.89 km/L [29], which we used in our calculations.

Results and discussion

CO_2 emission from producing Bio-coke

Table 3 shows the data collected to estimate the energy used in the relevant processes and each one's estimated CO_2 emission. CO_2 emissions per ton of BIC associated with manufacturing and transportation were calculated to

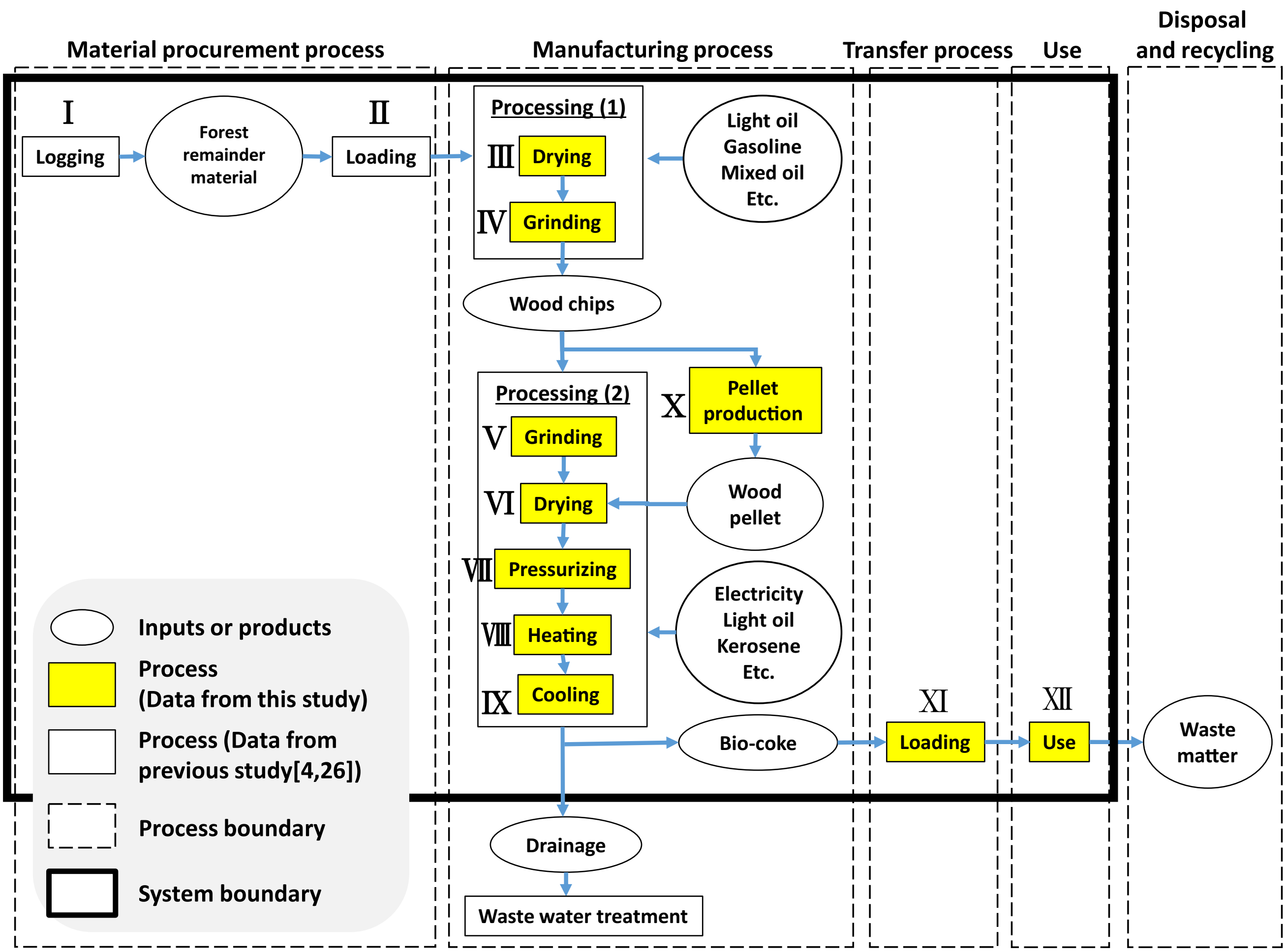

Fig. 2 System boundaries. Pellet production processes involve I–IV and X. BIC production processes involve I–IX. Details of the pellet manufacturing process are omitted in the figure and summarized inprocess X

Table 1 CO_2 emission factors

Energy	CO_2 emissions factors (t CO_2)	Unit
Electricity	5.16×10^{-4}	kWh
Light oil	2.58	kL
Kerosene	2.49	kL
Gasoline	2.32	kL
LP gas	3.00	t
Mixed oil	2.32	kL
Multi-diesel oil	2.89	kL
Coal-coke	3.17	t

Gasoline's CO_2 emission factor was used for that of mixed oil, because mixed oil is mostly gasoline. Lubricating oil's CO_2 emission factor was used for that of multi-diesel oil, because it is used as a typical lubricating oil for heavy equipment [19, 20]

Table 2 Calorific value per unit

Energy	Calorific value (MJ)	Unit
Electricity	3.6	kWh
Light oil	37.7	L
Kerosene	36.7	L
Gasoline	34.6	L
LP gas	50.8	kg
Mixed oil	34.6	L
Multi-diesel oil	40.2	L
Pellets	17.6	kg

Gasoline's calorific value was used for that of mixed oil, because mixed oil is mostly gasoline. Lubricating oil's calorific value was used for that of multi-diesel oil, because it is a typical lubricating oil for heavy equipment [23, 24]

be 1.01 ton-CO_2. CO_2 emissions from the manufacturing, obtaining raw materials, and sales and distribution processes are 91.3, 7.0, and 1.7 %, respectively. Notably, CO_2 emissions from Processing (2) account for 82.8 % of the total emissions. The processes involved in Processing (1) and (2) accounts for the large portion of overall CO_2 emissions.

Table 3 Energy consumed and CO_2 emitted to produce 1 ton of Bio-coke

Process		Item	Amount	Unit	t CO_2	(%)
Input						
Raw material						
Energy		Chips for 1 t Bio-coke	8.33×10^0	m^3	–	–
Obtaining raw wood material for chips (9.93 m^3)	Process I	–	–		6.44×10^{-2}	7.0
	Process II				5.91×10^{-3}	
Manufacturing	Processing (1)	Light oil	3.26×10^1	L	8.41×10^{-2}	8.4
	(producing 9.93 m^3 of chips)	Gasoline	1.39×10^{-1}	L	3.22×10^{-4}	
	Process III, IV	LP gas	6.72×10^{-5}	t	2.02×10^{-4}	
		Kerosene	3.32×10^{-2}	L	7.71×10^{-5}	
	Processing (2) (Producing 1 t Bio-coke) Processes V–X	Electricity	1.46×10^3	kWh	7.50×10^{-1}	82.9
		Light oil	1.49×10^0	L	3.85×10^{-3}	
		Kerosene	8.21×10^{-1}	L	2.05×10^{-3}	
		Multi-diesel oil	5.28×10^{-3}	L	1.53×10^{-5}	
		Pellet	2.00×10^{-1}	t	7.65×10^{-2}	
Product transfer	Process XI	Light oil	6.78×10^0	L	1.75×10^{-2}	1.7
Output product	Process XII	Bio-coke	1.00×10^0	t	0	0.0
Total amount				t CO_2	1.01×100	100

Energy-related information was obtained from interviews with OFOA personnel. CO_2 emissions associated with raising raw materials are from previous research [25]. CO_2 emissions arising from chip production are not included for pellets

CO_2 emissions from electricity ware the largest source by energy type, accounting for 74.7 % of the total emissions and 90.1 % of Processing emissions (2) (Fig. 3). This shows that most of the CO_2 emissions come from electricity consumption. Given that about 80 % of the electricity from Kansai Electric Power Company (KEPCO) originates from thermal power generation using coal-coke [30]. CO_2 emission from electricity use tends to be high.

For comparison, a study by the new energy and industrial technology development organization (NEDO) estimates CO_2 emissions from BIC production processes, focusing particularly on electricity consumption, assuming that recycled tips are used as raw materials [24]. It reveals that theoretically, 1355 kWh of electricity is needed to produce 1 ton of BIC. Using the values in Tables 1 and 3, CO_2 emissions from BIC production are estimated to be 0.70 t CO_2/t. In our study, electricity consumption and associated CO_2 emissions per ton of BIC produced under the same conditions are 1460 kWh and 0.75 t CO_2, respectively.

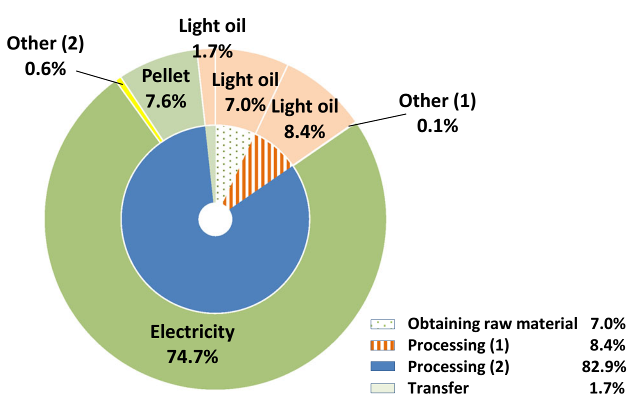

Fig. 3 CO_2 emissions by energy type and process. As "fuel" accounts for less than 1 %, it was included in "other". Other (1) includes gasoline, LP gas, and kerosene. Other (2) includes kerosene, multi-diesel oil, and pellets

Comparison to wood pellets

We performed a study comparing BIC and wood pellets as similar wood biomass fuels in terms of the environmental impacts, NEB, usability, and costs associated with their production. Both are being manufactured at the OFOA facility. The system boundaries for the comparative analysis are based on processes I–X in Fig. 2. We excluded the transportation process, because our aim was to compare the two up to production at the Takatsuki factory.

Based on interviews with OFOA personnel, the calorific values of wood pellets and BIC are 4200 and 4438 kcal/kg, respectively. Thus, there is not much difference between the two products in terms of calorific values, as both are made from the same raw materials. On the other hand, BIC is compressed densely, which allows it to be burned stably for a longer time. Thus, BIC can be used as alternative to coal cokes. CO_2 emitted in the processes of pellet production is estimated to be 0.51 t CO_2/t, meaning that its environmental load is lower than that of BIC (Fig. 4). This is attributed to the fact that more electricity is consumed in the production of BIC than that of wood pellets.

Next, we compared the NEB of BIC and wood pellets. The NEB is a value obtained by subtracting the input energy at the time of fuel purification from energy of the fuel produced. This is an indicator of efficiency and an environmental performance of produced energy. We calculated the calorific value per unit (MJ/t) based on 1 MJ being equal to 239 kcal. In this calculation, we again focus on the processes involved in producing both products, excluding transportation (process XI). We found that 0.27 and 0.6 MJ of energy is input for wood pellets and BIC, respectively, to generate output energy of 1 MJ (Fig. 5). More specifically, the NEB ratio for wood pellets is 3.67 while that of BIC is 1.67. We then consider the usability of the two products. The specific gravity of the pellets is between 0.6 and 0.7 while BIC's is between 1.2 and 1.4. This is mainly because the BIC is compressed more densely than the pellets. This also means that BIC has a higher energy density, which allows more efficient transportation. Furthermore, BIC can burn stably for long hours because it is compressed very densely. Because of these characteristics, BIC can be used in a blast furnace as an alternative to coal-coke. Thus, BIC can be expected to be used as an industrial heat source (note that BIC is transported to a company in Aichi Prefecture as an alternative fuel).

We then attempt to make rough estimates of production costs based on the costs of raw material, electricity, and fuel used in the processes (Table 4) for a comparison purpose. Note that we pay attention to costs for raw materials and energy consumption to simplify the estimation. Raw materials are thinned wood from the OFOA and industrial wood waste from other sources. Based on our interviews with OFOA personnel, the purchase price of thinned wood from the forestry section of OFOA is 6500 yen/m^3. We found that the thinned wood accounts for less than 5 % of the total raw materials. The majority of raw material comes from industrial wood waste, for which disposal fees can be obtained instead. We therefore did not include the cost of purchasing raw materials from OFOA in the estimation, as it is almost negligible. The fees for waste disposal vary depending on the type of material, such as branches, trunks, or root parts. We assumed that wood branches are the industrial wood waste most used as a raw material and applied their price of 18,000 yen/t as listed in the OFOA price list [31]. Production cost was calculated from usage and each price, the cost of electricity was obtained from interviews with OFOA and we used the price of fuel as of April 2013, available from the data of agency for natural resources and energy [32], along with information on the amount of fuel used. According to the OFOA, the water bill is between 3000 and 4000 yen per month for the entire plant, so we concluded that the cost for water is relatively small given the amount used and did not include it in the estimation. Again, personnel expenses and initial and maintenance costs of the facilities were excluded as well, because we focused only on the costs for raw

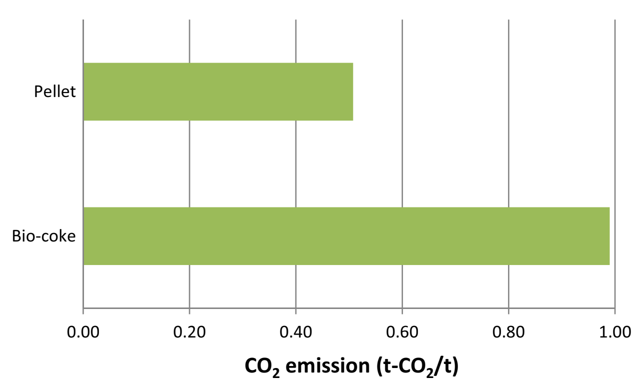

Fig. 4 Comparison CO_2 emission of Bio-coke (BIC) and pellet in the factory of Takatsuki. Product transport process is not included in this data

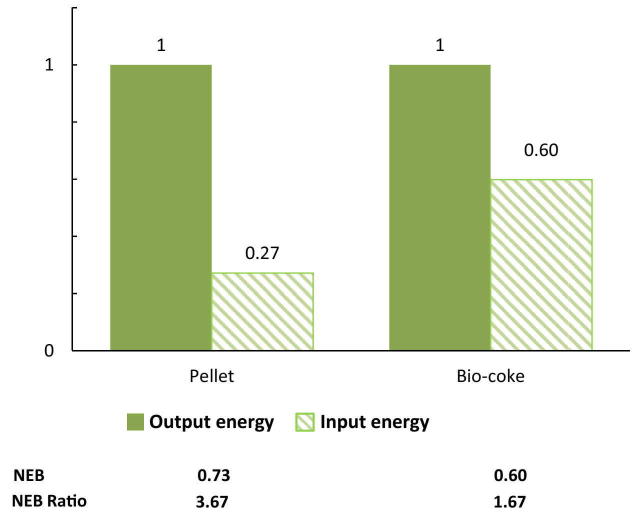

Fig. 5 Comparison net energy balance (NEB) of BIC and pellet in factory of Takatsuki. Product transport process is not included in this data

Table 4 Costs and selling prices of Bio-coke and pellet

	Pellet	Bio-coke
Cost of raw material (yen/kg)	−18	−18
Cost of production (yen/kg)	40.8	28.0
Total cost (yen/kg)	22.8	10.9
Selling price (yen/kg)	46	50

Raw materials are collected with fees for waste disposal. This can be counted as revenue, and is therefore shown as a negative value in the table materials and energy consumption for simplicity. We found that the costs of producing wood pellets and BIC are 22.8 and 10.9 yen/kg, respectively. Their selling prices are 46 yen/kg for pellets and 50 yen/kg for BIC. From this analysis, we argue that BIC has a higher gross margin than pellets when production is completed.

Overall, producing Bio-coke is less efficient in terms of energy consumption and CO_2 emission than producing pellets. Nonetheless, BIC has many benefits such as higher usability and gross margin. Above all BIC can be used in blast furnaces as alternative to coal-coke. If such alternative energy use is established, there is potential for high demand potential in the future.

Effects of CO_2 emission reduction using BIC as alternative fuel

The Bio-coke produced in the plant is used as an alternative to coal-coke at a company in Aichi Prefecture. BIC is a carbon-neutral fuel so its CO_2 emissions are not counted at the time of combustion. In other words, use of BIC could avoid CO_2 emissions that would otherwise have been created using coal-coke. Indeed, Uchiyama et al. [16] indicates that about 3100 tons of CO_2 can be avoided if 1000 tons of coal-coke is replaced by Bio-coke. As indicated in Table 5, 1 ton of BIC can substitute for 0.6 tons of Coal-coke in terms of calorific value and could avoid the emission of 1.86 t CO_2. However, these values do not take the CO_2 emitted to produce the BIC into account. We thus proceed to clarify the benefits and merits of using BIC by taking into account the CO_2 emissions from all the processes involved in BIC production and its use as an alternative to coal cokes.

The CO_2 emitted in producing and transporting BIC is 1.01 t CO_2/t, and we assume 0 t CO_2/t at the time of combustion because BIC is counted as carbon neutral. The CO_2 emission factor for coal-coke in this study is 3.17 t CO_2/t (Table 1). We estimate that one ton of BIC as an alternative to coal-coke can avoid 2.16 t CO_2/t. Calculated in MJ, 10.82×10^{-2} kg CO_2/MJ are produced for coal-coke and 5.44×10^{-2} kg CO_2/MJ for BIC. This means that using 1 MJ of BIC is equivalent to avoiding 5.38×10^{-2} kg of CO_2 emissions.

Conclusion

In this study, we clarified the CO_2 emission as an indicator of environmental impacts and overall benefits of producing and using BIC by looking into the case of a BIC plant in Takatsuki city, Osaka. From the analysis, we conclude the following points:

Most of the CO_2 emissions associated with BIC production originates in electricity consumption in the production process. Therefore, achieving reductions in electricity consumption by reviewing the relevant processes will be of vital importance in terms of reducing CO_2 emissions. It is important to note that though CO_2 emission is assumed during production, as analyzed in the study, alternative use of BIC as fuel can result in a 60 % emission reduction compared to using coal-coke. If cascade recycling of wood becomes a more common source of raw materials, larger CO_2 reductions can be expected in the future.

Pellet fuel, produced in the same facility as the BIC, has about the same calorific value as BIC. Pellets have some advantages over BIC in terms of environmental impacts but BIC has higher gross margin and energy density, which make it ideal for industrial uses like being substituted for coal-coke as described in this study. Pellets might be more suited to use in households and small facilities. Thus, it is essential for these biomass products to be utilized in suitable conditions and purposes, maximizing their merits and usability.

In Japan where forest accounts for 70 % of the country's area, the maintenance of forests has been a very serious problem. Using lumber from forest thinning as a raw material for producing BIC and wood pellets, which could lead to better forest maintenance, has promise in this regard, if their production is promoted. In order to promote forest biomass utilization, considering only environmental aspects is not enough. As mentioned earlier, environmental conservation, economy activity, and area fixity are needed to sustain forestry. BIC, for example, is promising in that if used in industry it can effectively contribute to both environmental conservation and economy activity. In the case of Takatsuki, Osaka, it is important that the OFOA produces BIC and pellets. Even if production increases rapidly with possible growth of demand, the OFOA will maintain a certain level of environmental concern and area fixity, rather

Table 5 Comparison Bio-coke and coal-coke

	Bio-coke	Coal-coke	Data source
Calorific value (kcal/kg)	4438	7000	OFOA interviews
Calorific value (MJ/t)	18,570	29,289	
CO_2 emission during production and transport (t CO_2/t)	1.01	3.17	Bio-coke: this study
CO_2 emission during combustion (t CO_2/t)	0		Coal-coke: [19]
Fuel amounts with equivalent calorific content (t)	1	0.6	–

than giving too much priority to economic considerations (profits). We argue that if forest biomass utilization is vigorously promoted, regional forestry will be revitalized in an effective and sustainable manner, which may positively impact the local area. The promotion of BIC production, then could have positive effects on environmental conservation, economy activity, and area fixity through the use of local resources. It has the potential to contribute not only to resolving global environmental problems, but also to improving Japanese forestry and local sustainability.

Acknowledgments The authors are grateful to the Osaka Prefecture Forest Owners Association, Japan, for providing useful information and data that enabled us to carry out this study.

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