Sustainability **2013**, *5*, 1188-1207; doi:10.3390/su5031188

OPEN ACCESS

sustainability

ISSN 2071-1050

www.mdpi.com/journal/sustainability

Article

Towards More Sustainable Ironmaking—An Analysis of Energy Wood Availability in Finland and the Economics of Charcoal Production

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Received: 5 February 2013; in revised form: 5 March 2013 / Accepted: 6 March 2013 / Published: 19 March 2013

Abstract: Replacement of fossil carbon by renewable biomass-based carbon is an effective measure to mitigate CO_2 emission intensity in the blast furnace ironmaking process. Depending on the substitution rate of fossil fuels, the required amount of biomass can be substantial. This raises questions about the availability of biomass for multiple uses. At the same time, the economic competitiveness of biomass-based fuels in ironmaking applications should also be a key consideration. In this assessment, availability of energy wood, *i.e.*, logging residues, small-diameter wood and stumps, in Finland is discussed. Since biomass must be submitted to a thermochemical process before use in a blast furnace, the paper describes the production chain, from biomass to charcoal, and economics related to each processing step. The economics of biomass-based reducing agents is compared to fossil-based ones by taking into account the effect of European Union Emissions Trading System (EU ETS). The assessment reveals that there would be sufficient amounts of energy wood available for current users as well as for ironmaking. At present, the economics of biomass-based reducing agents in ironmaking applications is unfavorable. High CO_2 emission allowance prices would be required to make such a scheme competitive against fossil-based reducing agents at current fuel prices.

Keywords: blast furnace; ironmaking; forest chips; reducing agent; charcoal; economics; CO_2 emission allowance price

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1. Introduction

Renewable energy plays an important role in the European Union's energy policy towards attaining a carbon-lean economy. The objective of the EU is to increase the amount of renewable energy to 20% on average of final energy use and to decrease the amount of greenhouse gases by 20% compared to the base year (1990) by 2020 [1]. In Finland, the target share of renewable energy is 38% of final energy use by 2020. According to the Finnish plan of action, the majority of the increase in renewable energy should come from the use of wood-based biomass in heat and power production [2].

One newly introduced concept that could contribute to the European Union's bioenergy objectives could be the use of biomass as a CO_2-neutral fuel and reducing agent in the metallurgical industry [3]. Previous research has been concentrated on the evaluation of the technological suitability of biomass-based reducing agents in metallurgical processes. Detailed analysis of charcoal characteristics and behavior in simulated process conditions can be found from the literature [4,5]. Babich *et al.* [6] and Mathieson *et al.* [7] have evaluated the possibility of using charcoal injection to replace pulverized coal injection in blast furnace by using mathematical modeling. Suopajärvi and Fabritius [8] have evaluated the plant site energy and environmental effects of biomass-derived charcoal use as a reducing agent in integrated steelworks. Norgate and Langberg [9] and more recently Norgate *et al.* [10] have investigated the life cycle effects of charcoal use in iron and steelmaking.

In addition to the technological suitability of biomass-based reducing agents, there are other factors that must be considered as well. Biomass availability is one possible factor curtailing the introduction of renewable energy in ironmaking. Also the cost of biomass and the cost of derived charcoal are factors that influence the adoption of new raw materials. Studies concentrating on the availability of biomass and possible production chain structures for ironmaking applications are scarce in the scientific literature. The supply potential of biomass for the steel industry has been evaluated by Piketty *et al.* [11] in a Brazilian context. In their analysis they evaluated the land availability requirements for producing charcoal for the Brazilian steelmaking industry. In Western countries no studies of available biomass sources for use in iron and steelmaking applications have been made.

In this paper the pathway to a bio-based reducing agent utilization scheme in Finnish ironmaking is described, from wood-based raw materials to application in the blast furnace. The paper provides an availability assessment of domestic logging residues, stumps and small-diameter wood (defined here as energy wood), with analysis of competing uses of raw materials based on the recent literature. An economic assessment of charcoal production is presented with comparison of fossil reducing agent costs at different CO_2 allowance prices.

2. Background of Biomass Use in Blast Furnace Ironmaking

2.1. Reducing Agent Use in Ironmaking

The production of steel in integrated steel plants that utilize the blast furnace (BF)-basic oxygen furnace (BOF) route is based on the use of virgin raw materials, e.g., iron oxides and coal. The blast furnace is a counter-current shaft furnace where solid materials descend and gases ascend. The reduction of iron oxides into hot metal is based on direct reduction with carbon and indirect reduction with carbon monoxide and hydrogen. In modern blast furnaces the consumption of coke is

around 300–350 kg per tonne hot metal (kg/tHM) and the consumption of pulverized coal in the range of 150–200 kg/tHM [12]. The produced hot metal is refined into steel in BOF and forwarded on to further refining processes, casting and rolling.

Research on the substitution of fossil reducing agents in ironmaking has strongly focused on the blast furnace, where biomass and more precisely, charcoal could replace: (1) a portion of the fossil coal in metallurgical coke production [13], (2) a small portion of the top-charged coke [14], or (3) pulverized coal in tuyere injection [6,7]. Current research findings suggest that the share of charcoal in coal blend could be around 5% without degrading the quality of the metallurgical coke [13]. According to Hanrot *et al.* [14] 20 kg/tHM of top-charged coke could be substituted with lump charcoal. By using charcoal for the substituting auxiliary injectant, the share of renewable reducing agent could be even 200 kg/tHM [6,10,15]. Table 1 presents possible fossil-based reducing agent substitution rates with charcoal addition in blast furnace ironmaking. Additionally charcoal could replace recarburizer carbon in basic oxygen furnace [15].

Table 1. Possible fossil-based reducing agent substitution rates in blast furnace with charcoal (based mainly on references [10] and [15]).

Application and replaced carbon source	Typical addition rate [1,2]	Charcoal substitution rate (%) [1,2]	Charcoal amount (kg/tHM)
Cokemaking (coking coal)	480–560 kg/tHM [3]	2–10	9.6–56 kg/tHM
BF tuyere injection (pulverized coal)	150–200 kg/tHM	0–100	0–200 kg/tHM
BF nut coke replacement	45 kg/tHM	50–100	22.5–45 kg/tHM
BF briquette [4] (coking plant residues)	10–12 kg/tHM	0–100	0–12 kg/tHM
Sintering solid fuel [5]	76.5–102 kg/tHM	50–100	38.3–102 kg/tHM
Pre-reduced iron ore composite pellets [6]	Not currently practiced		18–36 kg/tHM

[1] Norgate *et al.* [10]; [2] Mathieson *et al.* [15]; [3] 300–350 kg/tHM coke rate is assumed, coal to BF coke ratio of 1.6 is assumed; [4] Coke dust from the coking plant is used as carbon source in cold-bonded briquettes; [5] Sinter is not used in Finnish blast furnaces, but iron ore pellets. It is assumed that 1.7 t sinter is used to produce t hot metal (tHM) [15]; [6] According to Norgate *et al.* [10] not currently practiced, however 5–10% of iron in blast furnace feed could be replaced with pre-reduced iron ore composite pellets [15].

2.2. Thermochemical Conversion of Biomass into Reducing Agent

Biomass as such is not a suitable option for substituting large amounts of fossil fuels in reducing agent use in industrial applications because of its high moisture and oxygen content and low calorific value [16]. Low calorific value results in low fossil fuel replacement ratios in the blast furnace process. At minimum, raw biomass must be torrefied before injecting into the blast furnace [17]. Greater fossil fuel replacement ratios, however, can be achieved by using charcoal as a substituting fuel [6,7,15].

Thermochemical conversion processes are used to enhance the properties of biomass for use. According to Goyal *et al.* [18] thermochemical conversion processes include combustion, gasification, liquefaction, hydrogenation and pyrolysis. In slow pyrolysis, biomass is pyrolyzed at slow heating

rates, which results in increased char formation. The properties of charcoal are well comparable to the pulverized fossil coal used as an injected reducing agent in the blast furnace [6,7,15], some being even better. High carbon contents can be attained, although at the expense of the charcoal yield. Typically the yield of charcoal from wood with slow pyrolysis is around 28–35% when pyrolysis temperature is between 400–500 °C [19,20]. The higher heating value (HHV) of charcoal can be as high as 35 MJ/kg [20].

Several pyrolysis technologies have been developed, ranging from ancient earth pits to modern continuous-type screw reactors. Continuous retorts and screw-type reactors usually achieve 25–35% yield [21]. Charcoal yields are typically determined by the applied feedstock, pyrolysis temperature and reactor type, but with novel processes, such as flash carbonization, 40–50% yields can be achieved [22]. Even though charcoal has been produced for centuries, charcoal production technology is still nascent and large-scale charcoal production plants are scarce.

2.3. Biomass-Based Reducing Agent Requirements in the Finnish Carbon Steel Industry

In Finland, there is one production site based on the integrated Coking plant-BF-BOF route, Ruukki Metals in Raahe, located on the northern shore of the Gulf of Bothnia. Hot metal production is done with two medium size (1,200 m^3) blast furnaces [23]. At Ruukki, in addition to top-charged coke, extra heavy bottom oil is used in the blast furnaces as an auxiliary-injected reducing agent. The coke consumption in Finnish blast furnaces is around 385 kg/t hot metal on average, with oil consumption around 80 kg/t hot metal [23]. Biomass-derived charcoal could substitute for a small fraction of the top-charged coke or coal in metallurgical coke production, and small amounts could be used in the injected oil in Finnish blast furnace ironmaking. The alternative for oil injection system is pulverized coal injection system, which would allow larger charcoal amount introduction to the blast furnace. To present an indicative potential demand for wood-based biomass in Finnish blast furnace ironmaking, Equation 1 is proposed:

$$Y = \frac{m \cdot M}{\alpha \cdot \rho \cdot \eta} \tag{1}$$

where Y is annual green biomass requirement (Mm^3/year), m is the charcoal consumption (kg/tHM), M is the amount of annual hot metal production (Mt/year), α is the share of dry matter in wet wood, ρ is the density of wet wood (t/m^3) and η is the charcoal yield from oven dry wood.

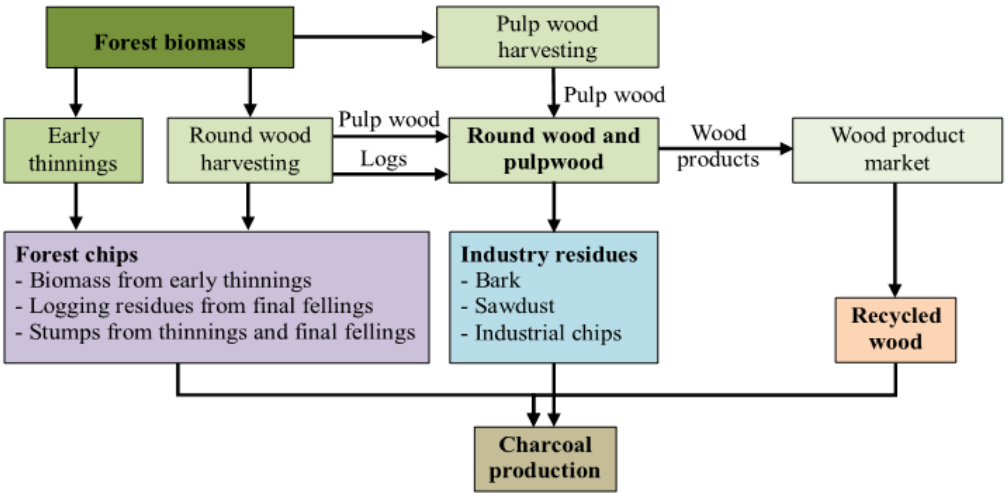
In a theoretical high-use scenario (*i.e.*, replacing of pulverized coal with charcoal based on the following assumptions: moisture of green wood 50%, density of green wood 0.85 t/m^3, yield of the charcoal from oven dry wood 30%, annual hot metal production 2 Mt and injected charcoal amount 150 kg/tHM), the annual charcoal need would be 300,000 tonnes. This would result in a yearly green wood requirement of 2.35 Mm^3, which represents more than 4.7 TWh in energy. This amount of wood, be it forest chips, pulp wood or demolition wood, while quite considerable, is an indication of the potential for using large amounts of biomass in the steel industry. In the transition towards a more sustainable steelmaking in Finland, smaller fossil reducing agent substitution rates are likely to be realized in the future. Availability of suitable raw materials, competition, price, and technology development have been identified as the major factors that will determine the implementation of bio-based reducing agents in the Finnish steel industry.

3. Biomass Availability for Ironmaking in Finland

3.1. Sources of Wood-Based Biomass

Wood resources in Finland are abundant and widely used in the pulp and paper industry and the energy industry. Solid biofuels include different solid fractions such as forest chips, bark, sawdust, industrial wood residues as well as liquid fractions such as black liquor. Today the majority of wood-based energy is recovered from liquid and solid industrial residues. Figure 1 presents the possible sources of wood-based raw materials for charcoal production and reducing agent production. The base raw materials consist of wood residues and theoretically would not be the target of competition by the pulp industry and the wood-processing industry.

Figure 1. Sources of feedstock applicable for reducing agent production purposes.



Solid residues from the wood-processing industry, *i.e.*, from the mechanical wood processing industry and pulp and paper industry, are utilized quite efficiently in Finland. By-products from sawmilling are used as raw materials in pulp production, particleboard and fiberboard production, pellet production and in the production of energy. Solid by-products from pulp production are mainly used in energy production. The existing wood processing chains are well-developed and integrated, which means that by-products of one plant are efficiently utilized by another plant.

As a result of the ambitious targets set by Finland to increase the use of wood fuels in energy production, several estimates of forest chip potential have been made in recent years, e.g., [24–26]. The availability estimates are usually divided into theoretical, techno-ecological and techno-economic potentials. In the theoretical estimates, it is assumed that the yield of logging residues and stumps is 100%. The theoretical potential also ignores the ecological aspects related to nutrient loss and economic restrictions. In the techno-ecological potential calculations, the yield of logging residues, stumps and thinnings is below 100%. Also, the willingness of forest owners to offer energy wood to markets is taken into account. Techno-economic potential estimates also take into account subsidies and energy producers' willingness to pay [26].

In this paper forest chip availability for steel industry in Finland is examined via a summary of recent energy wood availability assessments. Besides the traditional use of forest chips in energy

production, there are other, developing industries that would also utilize forest chips as raw materials. There are several bio-oil production plant projects under consideration in Finland, and there is also interest in constructing Fischer-Tropsch plants [2].

3.2. Forest Chip Potential in Finland

Logging residue refers to tree tops and also stem wood residues that are left in the forest after a timber harvesting. Logging residues are produced only from final fellings. Logging residue potential in a study conducted by Maidell *et al.* [25] is based on the commercial cuttings done in 2006. Energy wood accumulation from logs is based on the coefficients provided by [27,28]. These coefficients are used to calculate the accumulation of residues from stem wood. The theoretical logging residue potential in Finland was determined to be 8.2 Mm^3 (16.2 TWh). Maidell *et al.* did not evaluate techno-ecological potential in their research, but techno-economic potential was estimated at 3.3 Mm^3 (6.5 TWh).

Kärhä *et al.* [26] used similar methodology to evaluate theoretical logging residue potential, but the coefficients used in the calculation of theoretical logging residue potential differ slightly from the ones used in the study of Maidell *et al.* [25]. Kärhä *et al.* [26] estimated future energy wood potential, for the year 2020, basing their estimates on the anticipated development of the Finnish forest industry and wood imports with three different future scenarios. According to their study, the theoretical potential of logging residues in Finland will be 23.7–31.5 TWh, *i.e.*, around 11.9–15.7 Mm^3. A recovery rate of 70% was used in the calculation of techno-ecological potential of logging residues from final fellings. Ecological constraints differed between 57–89%, depending on the regional forestry center. The Finnish Forest Centre is a governmental forestry organization that is divided into 13 regional forestry centers covering the whole country. Willingness to offer logging residues to market was assumed to be 90% for private forest owners and 100% for other forest owners. Techno-ecological potential in three different scenarios ranged from 11.4 to 15.0 TWh. In the three different future scenarios, techno-economic potential with defined restrictions (10.5–12.5 TWh) differs only slightly from techno-ecological potential.

A study by Hakkila [29] calculated that the theoretical potential of logging residues would be 14 Mm^3, *i.e.*, around 28 TWh, and that technically harvestable residue potential, taking into considering ecological constraints, would be 7.5 Mm^3, *i.e.*, 15 TWh. Pöyry Energy [30] has estimated the theoretical potential of logging residues in 2020 to be 16.8 TWh. Unlike many other theoretical potential calculations, in the Pöyry Energy study the recovery rate of logging residues from final fellings was 65%. The techno-economic potential in their study was found to be 7.8 TWh.

The use of stumps and roots in energy production has not been standard practice in Finland until the beginning of the 21st century [31]. In 2011 the share of forest chips produced from stumps was 14% in heat and power production. The collection of stumps for use in energy production has been premised on spruce stumps, which are easier to harvest and cause only a shallow hole in the ground, but in energy wood potential estimations also pine and birch stumps may be considered. Because of the heavy equipment required for uprooting, only final fellings and saw timber-sized trees are considered [29]. In a study by Maidell *et al.* [25] stump potential was defined based on the data about timber-sized cuttings from 2006. They used an average coefficient of 0.25 to calculate the amount of stumps from

the total saw log amount. The theoretical volume of stumps was calculated to be 5.9 Mm^3 (13.3 TWh); techno-economic potential was 2.2 Mm^3 (4.6 TWh).

Kärhä *et al.* [26] used coefficients ranging from 0.28 to 0.40 to calculate the amount of stumps from three final felling scenarios forecast in 2020. The theoretical stump potential in three different future scenarios was 22.9–30.3 TWh, which is comparable to logging residue potential. In the calculation of techno-ecological potential, the recovery rate was 85% for pine stumps and 90% for spruce and birch stumps. The ecological constraints for stump removal were set at 82–88% and considered separately for each forestry center. The willingness to offer stumps to market was assumed to be 70% for all the forestry centers. The resulting techno-ecological stump potential varied from 13.3 to 17.6 TWh. Techno-economic potential was estimated to be about 10 TWh for all three scenarios.

Hakkila [29] estimated that theoretical stump potential would be 15.0 Mm^3, *i.e.*, around 30 TWh, and that technically harvestable stump potential, with ecological constraints, would be only 2.0 Mm^3, *i.e.*, 4.0 TWh. Pöyry Energy [30] estimated theoretical potential of stumps in 2020 to be 18.6 TWh with a techno-economic potential of 5.3 TWh.

Small-diameter thinning wood is harvested in young stands for energy production. Small-diameter energy wood production has silvicultural benefits and represents a source for increasing the share of bioenergy in Finland. Several factors affect the selection of small-diameter wood stands for energy production from young stands. The diameter of the wood, accumulation of commercial wood per hectare and accumulation of energy per hectare are factors that are taken into account in energy wood potential calculations [30]. In small-diameter wood potential calculations, different assumptions were used depending on the source [25,26,28]. Energy wood potential calculations are based on the data from National Forest Inventories (NFI).

Theoretical small-diameter wood potential in Maidell *et al.* [25] was based on the amount of usable energy wood in seeding stands, young stands, improvement fellings, and in first thinning stages. The total theoretical potential was estimated at 13.4 Mm^3 (25.5 TWh). In Kärhä *et al.* [26] small-diameter energy wood potential calculation was based on data from the 10th National Forest Inventory provided by Finnish Forest Research Institute. Theoretical potential was estimated to be 53 TWh in all three scenarios. In the techno-ecological potential calculations, a recovery rate 95% was used for small-diameter wood. The ecological constraints were set at 57–89% and willingness to offer small-diameter wood to market was 80% for private owners and 100% for other owner groups. The techno-ecological potential was determined to be 15.7–25.0 TWh for three scenarios. The great difference between scenarios is the result of using different restrictions in the calculations for the suitable stands. Techno-economic potential varied between 6.5–8.5 TWh across the scenarios.

In the study of Hakkila [29] the theoretical potential for small-diameter wood was 16.0 Mm^3, *i.e.*, around 32 TWh, and the technically harvestable potential was estimated as 5.5 Mm^3, *i.e.*, 11.0 TWh. Pöyry Energy [30] estimated theoretical potential (in 2020) to be 17.2 TWh with techno-economic potential 7.0 TWh.

3.3. Competing Use of Forest Chips

In Finland the predicted share of renewable energy is set for 38% of final energy use in 2020 [1]. The majority of the increase in renewable energy is presumed to come from biomass sources by

increasing the amount of forest chip use in heat and power applications and also in transportation fuel production. Target forest chip use in Finland is set at 25 TWh for 2020. The goal for production of transportation fuels is 7 TWh, which implies approximately 12 TWh of logging residues [2]. Current and future demand for forest chips in other industries is one of the main factors that will determine the possibility of utilizing wood-based biomass for reducing agent purposes.

The energy industry is today, and will be also in the future, the largest user of forest chips. The use of forest chips in energy production has increased steadily in Finland. In 2000, the use of forest chips in heat and power plants was 0.8 Mm^3; the corresponding volume in 2011 was over 6.8 Mm^3 [32]. Kärhä *et al.* [26] have estimated that the capacity to utilize forest chips in energy production in 2020 would be 27.8 TWh, which implies that techno-economic forest chip potential and anticipated installed capacity in heat and power plants in 2020 would be at the same level. However, there are regions in Finland where supply and demand are not met. In some regions there is low demand for forest chips in energy production and possibly a surplus of raw material suitable for forest chips production. It has been estimated that the proposed increase in boiler capacity required for forest chip exploitation may not be easily adopted [26], which speaks for alternative uses.

Beside use in heat and power plants, there are various other users of forest chips in Finland now and likely will be in the future as well. Metso, VTT, Fortum and UPM have developed an integrated concept where fast pyrolysis is integrated with a fluidized-bed boiler to produce bio-oil [33]. At the moment, Metso is building the first industrial-scale integrated pyrolysis plant in Finland. The annual production capacity will be 50,000 tonnes of bio-oil, the forest chip need being 225,000 m^3 [34]. Additionally, a Finnish company called Green Fuel Nordic is going to construct at least one, but possibly three, bio-oil production plants in Finland during the next few years [35]. The annual capacity of each bio-oil plant will be 90,000 tonnes with an estimated raw material need of 350,000 m^3 of forest chips [36].

There is also growing interest in production of transportation fuels from forest chips in Finland. Three biodiesel projects were initially under consideration in Finland by two joint projects, Vapo and MetsäGroup, and Stora Enso and Neste Oil, with one project backed solely by UPM [2]. The plan was to produce second-generation biofuels from lignocellulosic biomass based on the gasification and Fischer-Tropsch synthesis. Only one of the advanced biofuel projects received renewable energy technology funding (NER300) in Finland [37]. The planned Biomass-to-Liquid plant in northern Finland would produce 115,000 tonnes of biodiesel and bionaphta annually. The raw material would be stem wood from first thinnings, chipped at the plant site. The required wood would be around 1.5 million cubic meters a year [38].

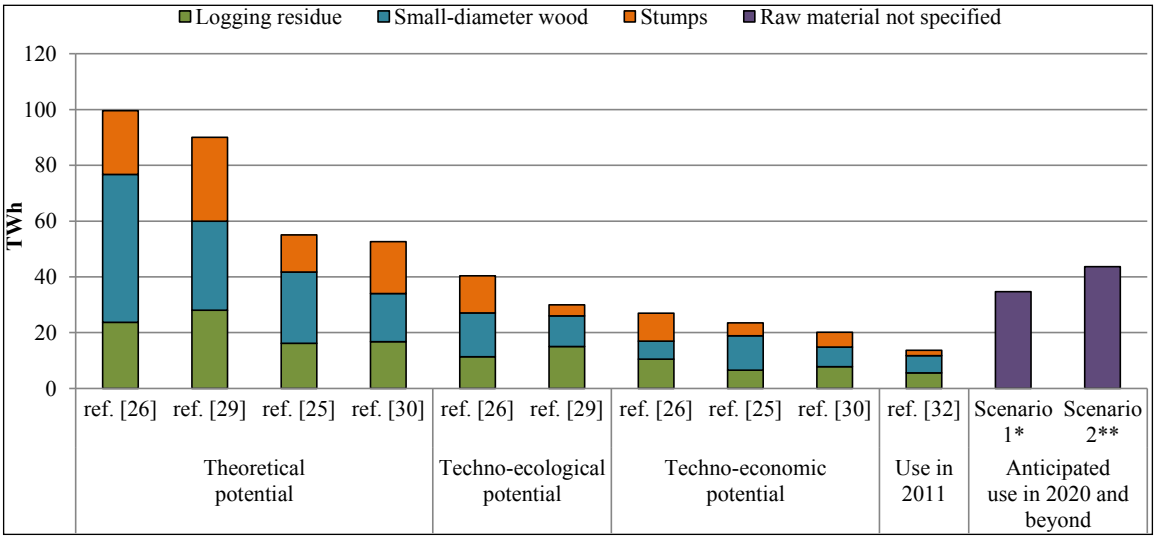
There are also other innovative projects in progress that would not increase the need of forest chips significantly, but are based on the more efficient use of pulp production by-products. UPM has started to construct the world's first wood-based biorefinery in Lappeenranta, Finland. The biorefinery will produce approximately 100,000 tonnes of second generation biodiesel from crude tall oil [39]. Additionally, Metsä Fibre, Gasum and Helsingin Energia are exploring the possibility of producing wood-based Bio-SNG (95% methane) from forest chips and bark. The estimated raw material need would be 1.3 Mm^3 with a plant production capacity of 200 MW Bio-SNG [40]. In addition, wood pellet production in Finland was 308 000 tonnes in 2011 [41]. The raw material for wood pellet production is mainly sawdust, a by-product from the saw mill industry.

Beside the above-mentioned competing uses, an industry to produce biomass-based reducing agents for ironmaking will also be required. As mentioned, forest chips should be at least torrefied, preferably pyrolyzed before injection into the blast furnace. At present no large-scale charcoal industry exists in Finland because there are no large-scale users in the market. The prospect of using renewable biomass in coal-fired power plants has resulted in growing interest in torrefied pellets [42], which might engender the development of an industry based on thermochemical conversion of biomass into more energy dense products alongside bio-oil production.

3.4. Summary of Forest Chip Production Potential

Forest chip potentials from four literature sources with differing background assumptions were evaluated. The data presented in this paper concerning different availability potentials in Finland is summarized as total availabilities in Figure 2. Figure 2 also summarizes the current use of forest chips in heat and power production and anticipated use in 2020 onwards. The minimum values from three different scenarios presented by Kärhä *et al.* have been selected. Theoretical forest chip potential is between 52.6–100 TWh in the reviewed studies. The biggest discrepancy in theoretical forest chip potentials revolves around the issue of small-diameter wood. Kärhä *et al.* [26] estimated that the theoretical potential is over 53 TWh, whereas the potential was only 17.2 TWh in the report by Pöyry Energy [30]. Differences in techno-economic potential, however, are smaller, 20.2–27 TWh, compared to theoretical potential. Anticipated use of forest chips in 2020 (Scenarios 1 and 2 in Figure 2) are based on the forecast of forest chip use in heat and power production [26] and other alternative uses [2,34,36,38,40].

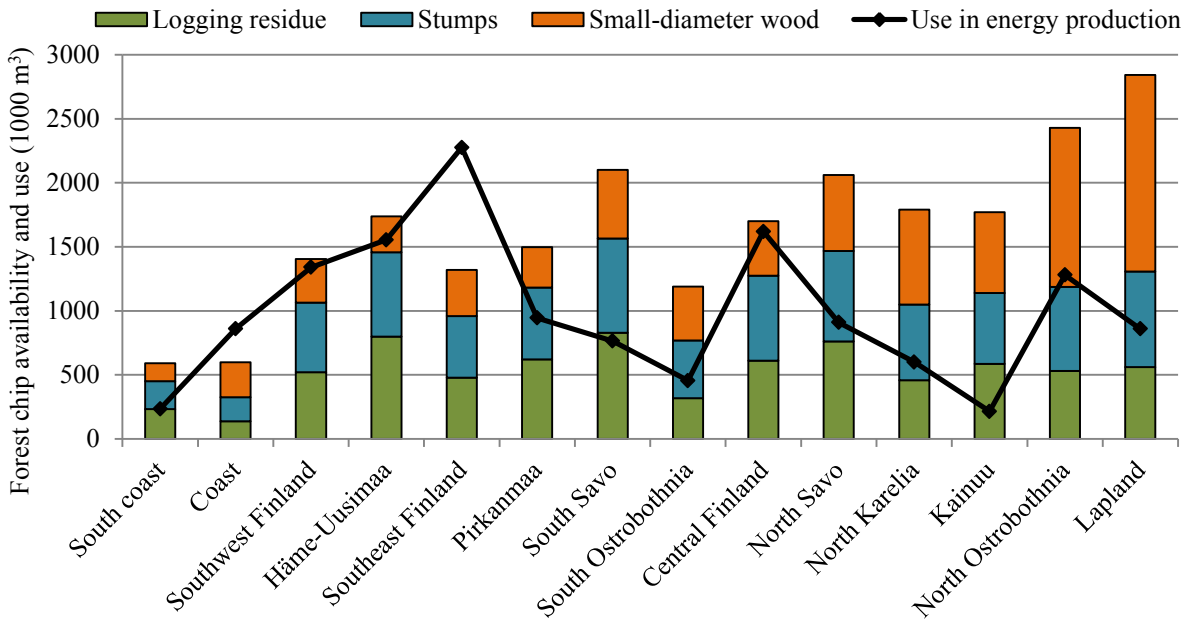
Figure 2. Theoretical, techno-ecological and techno-economic forest chip potentials in Finland; use of forest chips in 2011 in heat and power plants and anticipated use of forest chips in 2020 onwards.



* Assumptions in Scenario 1: Forest chip use in heat and power plants is 27.8 TWh [26]. There is one Fischer-Tropsch plant in Finland (forest chip use 3.0 TWh), four bio-oil plants (forest chip use 2.6 TWh) and large Bio-SNG plant (forest chip use 1.3 TWh, *i.e.*, half of the raw material need described in [40]); ** Assumptions in Scenario 2: As in Scenario 1, but there are three to four Fischer-Tropsch plants in Finland (forest chip use 12 TWh) as described in reference [2].

Forest chip potential is not evenly distributed in Finland. There are 13 forestry centers in Finland, which are considered as analysis units in many forest chip potential evaluations. In Figure 3 the anticipated (2020) techno-ecological potential of logging residues, stumps and small-diameter wood for forest chip production is presented for 13 forestry centers. The round wood harvest level is taken from Kärhä *et al.* [26] being 67.9 Mm^3. Logging residues and stumps are collected from final fellings, which consist of 70% of the round wood harvests. The coefficients used to calculate the theoretical accumulation of logging residues and stumps are from [27,28] and the share of tree species is assumed to be distributed as in 2007. In the calculation of techno-ecological potential of logging residues and stumps the coefficients provided by Kärhä *et al.* [26] have been used. Small-diameter wood potential is taken directly from the data provided by Kärhä *et al.* [26]. In Figure 3 the anticipated use in heat and power production in 2020 is also presented [26].

Figure 3. Estimated techno-ecological forest chip potential and use in energy production in 2020 (based on the data by [26]).



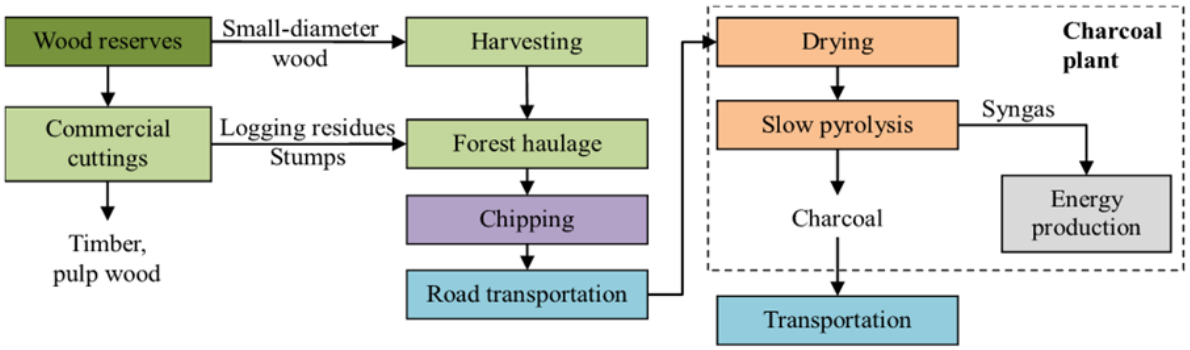
It can be seen that in some forestry centers the availability of forest chips is negative, whereas in others the availability is positive, especially in those forestry centers closest to the Finnish steel producers (Lapland, North Ostrobothnia, Kainuu, North Savo). Additionally, the planned use of forest chips in bio-oil and transportation fuel production should be included in the analysis. The techno-economic potential of forest chips is lower than techno-ecological potential, and according to Kärhä *et al.* [26] techno-economic potential and installed capacity in heat and power plants in 2020 will be at similar level. Availability of logging residues and stumps is heavily affected by forest industry production capacity, which has been at low levels in recent years. According to Kallio *et al.* [43], a sufficient amount of residues and stumps would be available for the energy industry if forest industry production rates return to the rates before the present economic crisis.

4. Economic Issues in Charcoal Production and Use in Ironmaking

4.1. Supply Chain Costs of Charcoal Production

In Section 2.2 it was addressed that forest chips should be treated with thermochemical conversion before injection into the blast furnace. In this section the costs related to charcoal production throughout the value chain from forest to final product are evaluated. As pointed out in the paper, there are basically four types of wood fractions available for forest chip production: logging residues, stumps, small-diameter wood and stem wood, which has quality flaws. A simplified flowsheet of charcoal production, from wood-based raw material to charcoal for blast furnace injection, is presented in Figure 4. Additionally, there might be need for an additional cleaning stage of the forest chips, if the raw material is contaminated by soil. Depending on the particular forest chip production chain, wood chipping can be conducted at the road side or at the charcoal production plant. Although there are no large-scale charcoal production plants in Finland, research has been conducted worldwide aimed at developing suitable pyrolysis reactors for charcoal production. One example of large-scale charcoal production technology is the Lurgi process. There is at least one such charcoal production plant, with 27,000 tonnes capacity, running in Australia [44].

Figure 4. Flowsheet of the charcoal production from raw material to final product.



The cost structure of forest chip production is different for logging residues, stumps and small-diameter wood. Several factors have an impact on the accumulation of costs, e.g., quality of the stand, forest haulage distance and productivity of the harvesting and haulage machinery [45]. The costs of charcoal production from forest chips cost can be presented as:

$$C_{Total} = C_{stump} + C_{FC\,prod} + C_{FC\,trans} + C_{CC\,prod} \quad (2)$$

where C_{Total} is the total production cost of charcoal, C_{stump} is stumpage price, $C_{FC\,prod}$ is production cost of forest chips (cutting, forwarding, chipping and overheads), $C_{FC\,trans}$ is forest chip road transportation costs and $C_{CC\,prod}$ is charcoal production stage costs. Extra cost might occur if forest chips require intensive cleaning stage. Because there is no available data in the literature concerning the costs of charcoal production throughout the whole value chain, the following sections are dedicated to examining the costs of charcoal produced from Finnish logging residues, which is the cheapest of the raw material types. Additionally, the cost of charcoal is compared to the cost of fossil-based reducing agents, taking into account the effect of a CO_2 emission trading scheme as well.

Forest chip cost at the roadside summarizes stumpage price and forest chip production costs in a case of roadside chipping supply chain. The majority of the chips from logging residues are produced by roadside chipping [46]. In many of the studies no stumpage price is allocated to logging residues [45]. In this study the stumpage price paid to the forest owner is assumed to be 1 €/m^3 [43].

Cutting and forest haulage costs depend on several factors. In the case of logging residue, cutting is not needed, but residues must be forwarded to roadside. The forest haulage cost for logging residues is around 6 €/m^3. Chipping costs are 6 €/m^3 and organizational costs are 3.5–4 €/m^3 [43,45,47].

Transportation costs of forest chips can become substantial when the transportation distance becomes long. Petty and Kärhä [47] have derived Equation (3) to calculate road transportation costs for chips produced from small-diameter wood for a load size of 42.5 m^3, which can be used also for logging residues. Loading and uploading of the truck is incorporated into the equation:

$$C_{FC\,trans} = 2.858 + 0.066x \quad (3)$$

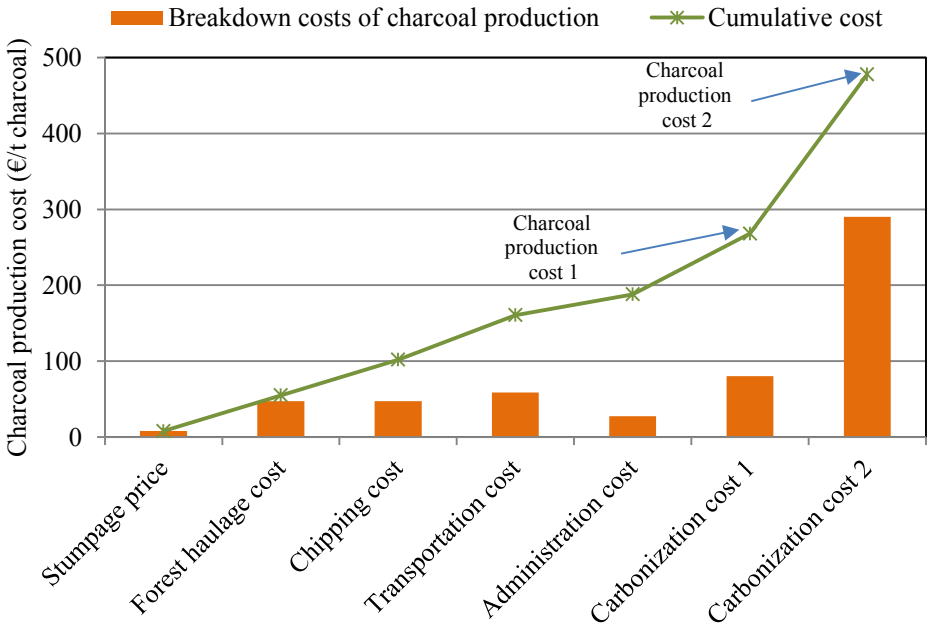
where $C_{FC\,tran}$ is road transportation cost, €/m^3 and x is road transportation distance in km. A theoretical transportation distance of 70 km is used in this study, resulting in transportation costs of 7.5 €/m^3.

Charcoal production stage costs are not widely discussed in the literature. Estimates of total charcoal production costs have been provided by e.g., Norgate and Langberg [9] and Noldin Jr [48]. Charcoal production costs in Australia based on the Lambiotte continuous retort technology were 386 US$/t charcoal [9], in Brazil 255 US$/t charcoal was reported [48]. Charcoal production stage costs are influenced by the applied technology, cost of utilities such as electricity, fuels, water and heat, labor costs and maintenance costs [49]. These costs vary depending on the country and also on the capacity of the plant. Norgate and Langberg cited a charcoal production stage (carbonization) cost of 113 US$/t charcoal in their paper [9] and around 60 US$/t charcoal was offered in a paper by Noldin Jr. [48]. In the work of Shackley *et al.* [49] production stage costs for three different size biochar production plants were given. Biochar can be seen as synonym for charcoal because both are produced with slow pyrolysis at temperatures above 400 °C. Production stage costs comprising capital, storage, utility, labor and other plant costs ranged from 65 to 235 GB£/t (98 to 353 US$/t) charcoal. The authors state that there is high uncertainty in the costs because of the absence of commercial slow pyrolysis plants in Europe.

4.2. Total Cost of Charcoal Production

Production of one tonne of charcoal from wood-based biomass requires almost 6.7 tonnes of raw material (wet basis, 50% moisture) when the yield of charcoal is assumed to be 30% in dry basis. This equals around 7.8 solid cubic meters of wood. The total forest chip costs calculated from the presented assumptions is 24 €/m^3. Multiplying this by the required volumes of green wood, the total cost of raw materials delivered to the charcoal plant would be 188 €/t charcoal. Charcoal production stage costs in developed countries reviewed in the paper, converted into euros, range roughly from 80 to 290 €/t charcoal [9,49]. In Figure 5 the costs related to charcoal production through the supply chain are presented for two of the above-presented charcoal production stage cost estimates. Columns represent the charcoal production costs of each stage of the production and a solid line represents the accumulated costs per produced tonne of charcoal.

Figure 5. Cost of charcoal production in Finland.



The analysis of the supply chain yields total charcoal production costs of 268 to 478 €/t charcoal from logging residues. The realistic charcoal production stage cost is likely to be somewhere between the presented values, thus resulting in a charcoal production cost estimate of below 400 euros per tonne. In this assessment no attention has been paid to utilization of by-products derived from slow pyrolysis. Syngas and various tars that could be sold for other purposes are formed in slow pyrolysis and could contribute significantly to revenues [49,50]. On the other hand, it must also be remembered that logging residues are the cheapest raw material for forest chip production and that their availability is limited. The techno-ecological availability of logging residues is around 7.4 Mm^3 in Finland and competition over the most economically feasible raw material fraction could be severe.

4.3. Charcoal Economics Compared to Fossil-Based Reducing Agents with CO_2 Cost

The steel industry's willingness to pay from biomass-based reducing agents has not been evaluated thoroughly in the literature before. As stated earlier, in blast furnace ironmaking top-charged coke and injected pulverized coal, oil, natural gas or waste plastics can be used as conventional reducing agents. The prices of these reducing agents differ and the willingness to pay for bio-based reducing agents depends on the substituted reducing agent. Use of charcoal in the blast furnace could also lead to other benefits than reduced fossil CO_2 emissions. Because of the basic ash chemistry of the charcoal, the amount of fluxes such as limestone and BOF slag could be decreased. This would result in lower slag amounts thus possibly leading to an increase in hot metal productivity in the furnace [6].

The economic comparison conducted in this paper does not take into account the possible productivity increase in the blast furnace, but reducing agents are compared, as such, to those fuels used in Finnish ironmaking today. The impact of carbon dioxide allowance prices is the only policy instrument that is discussed. Reducing agent consumption calculations in the blast furnace are kept simple and present the average values in the industry [12,23,51]. At present, coke and bottom oil are used as reducing agents in Finnish blast furnaces (Base case 1). Pulverized coal is used as an injected

reducing agent in a majority of the blast furnaces in the world, and this scenario is therefore duly evaluated (Base case 2). The economics of three different fossil-based reducing agent replacement scenarios are evaluated. In the first scenario, top-charged charcoal is assumed to replace 20 kg of coke with a coke replacement ratio of 1.0 [14]. In the second scenario, charcoal is assumed to replace a portion of the injected oil by adopting liquid-solid injection [52]. In the third scenario it is assumed that charcoal injection replaces pulverized coal injection entirely, which should be technologically possible [6,7,15]. Charcoal is assumed to replace higher share of coke in blast furnace than pulverized coal according to calculations presented by Mathieson *et al.* [15]. For the calculation of CO_2 costs, it is assumed that all the carbon entering the blast furnace is transformed into carbon dioxide. In reality, hot metal contains around 4.5% carbon, which is, however, removed in basic oxygen furnace to produce steel. The carbon content in coke and charcoal is 88%, for pulverized coal and oil it is 87%. In Table 2, the scenarios under economic evaluation are presented. All the values are presented per produced tonne of hot metal (tHM). CO_2 emission changes resulting from coke production rate as well as possible decrease in limestone consumption are ignored. The calculation procedure used here for CO_2 emissions is not fully comparable to calculation procedure defined for emission allowance calculations [53,54], but gives an overview of the possible effect of political incentives on the economics of ironmaking.

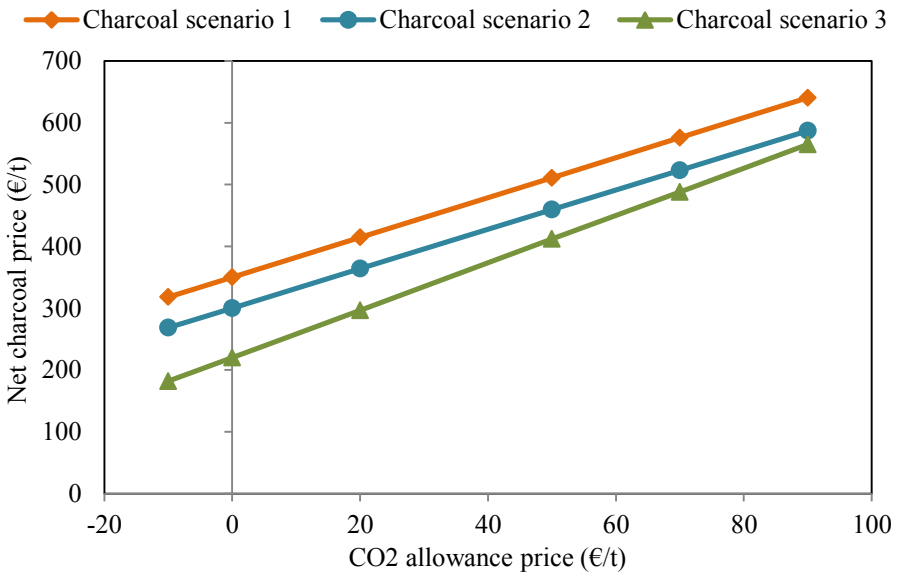
Table 2. Reducing agent consumptions and fossil CO_2 emissions.

	Base case 1	**Base case 2**	**Charcoal scenario 1**	**Charcoal scenario 2**	**Charcoal scenario 3**
Coke (kg/tHM) *	385	340	365	385	310
Bottom oil (kg/tHM)	80	-	80	66.5	-
Pulverized coal (kg/tHM)	-	150	-	-	-
Charcoal (kg/tHM)	-	-	20	13.5	150
Total reducing agent use (kg/tHM)	465	490	465	465	460
Emitted fossil CO_2 (kg/tHM)	1,496	1,574	1,432	1,453	1,000

* tHM stands for ton hot metal.

The price of pulverized coal presented in the literature is 130–200 €/t [55,56]. In this assessment 150 €/t is used. In the work of Helle *et al.* [57] a price of 150 €/t has been used for oil. In this work a higher price for oil is assumed (300 €/t) because of the increased price of heavy fuel oil compared to price level of 2009 [58]. The price of coke is assumed to be 350 €/t, taking shipping and other related costs into account [59]. Charcoal competitiveness against fossil reducing agents with variable CO_2 allowance prices is presented in Figure 6. A conservative estimate of the charcoal price in large-scale production plant could be around 400 €/t in Finland, assuming that revenues from the slow pyrolysis by-products would be fairly equivalent to profit demand of the charcoal producer. In Charcoal scenario 1, in which charcoal would replace a small portion of the top-charged coke, the break-even carbon dioxide allowance price would be 16 €/t CO_2. In Charcoal scenario 2, in which charcoal replaces a small portion of the injected oil, the break-even price for the CO_2 allowance would be around 31 €/t CO_2. In the last replacement scenario (Charcoal scenario 3), in which charcoal would replace injected pulverized coal, the break-even CO_2 allowance price is the highest, about 47 €/t CO_2.

Figure 6. Effect of CO_2 allowance price on the competitiveness of charcoal as reducing agent.



A significant rise in CO_2 allowance price is therefore needed before logging residue-based charcoal becomes competitive from the steel plant owner's perspective. If broader system boundaries and possible credits from pyrolysis by-products would be taken into account, more optimistic break-even CO_2 allowance prices would be achieved [9,10]. The fossil fuel replacement alternative closest to realization from the economic point of view would be partial coke replacement. However, this alternative represents only minor potential to decrease the amount of fossil CO_2 emissions. In the case of Ruukki, with 2 Mt hot metal production, the annual CO_2 reduction potential would be 0.13 Mt compared to Base case 1, which presents the current practice. In Charcoal scenario 2, the fossil CO_2 emissions would drop by 0.09 Mt compared to Base case 1. Base case 2, where solid pulverized coal is injected instead of oil, offers larger CO_2 reduction potential. In Base case 2 the total CO_2 emissions in the blast furnace would increase compared to Base case 1 because of the lower coke replacement ratio of pulverized coal than bottom oil. The annual CO_2 potential in Charcoal scenario 3 compared to Base case 1 is 0.99 Mt, and 1.15 Mt compared to Base case 2. The green forest chip demands in the three replacement scenarios are 0.21, 0.31 and 2.35 Mm^3 respectively. In Charcoal scenario 3 the potential to replace pulverized coal with charcoal ranges from 0 to 100%, so the figure presented here shows the maximum forest chip demand.

5. Discussion and Conclusions

It is clear that the high amount of biomass available from forestry could constitute a significant resource for bioenergy and other applications in Finland. In this study an alternative approach to contributing to renewable energy and CO_2 emission reduction targets has been discussed. Wood-based biomass application as a CO_2-neutral reducing agent could possibly contribute a significant share in the planned increase in solid wood fuel utilization in energy production.

In the study, recent estimations of forest chip potentials were reviewed [25,26,29,30] to determine whether there is true potential to use biomass also in the steel industry. The availability estimations differed quite significantly, predominantly due to the assumptions made in the potential calculations. It

seems that there would be an installed capacity in Finnish heat and power plants that could make use of 27 TWh of forest chips as fuel in 2020. Additionally, possible bio-oil and biodiesel plants could use significant amounts of forest chips. However, techno-ecological potential estimations show that there would be excess forest chips available near the steel plants.

Supply chain cost calculations revealed that biomass-derived charcoal is not far from being feasible if used as a substitute for metallurgical coke or heavy bottom oil in reducing agent application. CO_2 emission reduction potential is modest in the case of Ruukki, from 0.09 to 0.13 Mt annually, but the required CO_2 emission allowance price is modest: 16 and 31 €/t CO_2 respectively when charcoal price is 400 €/t. The present CO_2 emission allowance prices do not support charcoal to substitute pulverized coal injection in the blast furnace. With a charcoal price of 400 €/t and pulverized coal price of 150 €/t, the CO_2 allowance price should be almost 50 €/t CO_2 to reach the break-even point. Comparing biomass use to other CO_2 emission mitigation strategies used in the steel industry, such as Carbon Capture and Storage (CCS), one can see that high emission allowance prices are needed in that option too, break-even prices reaching a level of 72 €/t CO_2 in the most favorable option with current solvent technology [60]. The costs for avoided emissions with CCS are sensitive to several factors, e.g., electricity price, used solvents, captured CO_2 amount and selected system boundaries [60].

Biomass use in the blast furnace ironmaking process could provide a sustainable option for decreasing the amount of fossil CO_2 emissions. The share of wood-based charcoal could be gradually increased in the BF process, which makes it a flexible alternative. The needed investments in the steel plant infrastructure would be modest compared e.g., to the CCS option. The preliminary results encourage conducting more detailed analysis of the availability of forest chips under competition as well as for a wider-range of raw materials.

Acknowledgments

The authors acknowledge the financial support provided by the Finnish Funding Agency for Technology and Innovation (Tekes), Finnish companies and associations in the Bioreducer project, as well as the Graduate School in Chemical Engineering (GSCE). The valuable comments of Docent Eva Pongrácz are also greatly acknowledged.

Conflict of Interest

The authors declare no conflict of interest.

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