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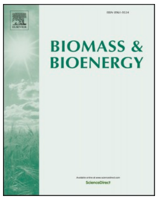

# Recycling of ash from co-incineration of waste wood and forest fuels: An overlooked challenge in a circular bioenergy system

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ABSTRACT

Wood ash recycling to forests after logging residues harvest is important to ensure long-term sustainable forest management, however, it is not recycled in Sweden at the level required to compensate for current logging residue out-take. A problem in this context is wood ash contamination through co-incineration of waste wood with forest fuels, a practice driven by the political goal of a circular bioenergy system. We performed a case study of co-incineration at a typical Swedish district heating (DH) plant, which showed that the forest fuel ash alone could be recycled to forests due to high nutrient levels. Co-incineration with waste wood resulted however in such high levels of contaminants that the ash was landfilled as hazardous waste. Our assessment of the Swedish DH sector showed that wood ash contamination through co-incineration is common, and that only a minor proportion of the ash from forest fuels is recycled to the forest. It also revealed a lack of reliable data regarding ash production and management, making implementation and evaluation of effective countermeasures difficult. Practical measures to enable wood ash recycling, such as removal of waste wood from the fuel mix, incineration of separate fuels, and ash after-treatment, are hampered by technical and economic barriers. Furthermore, no comprehensive policy tools currently exist on either a national or EU level that facilitate wood ash recycling. Thus, we conclude that comprehensive and efficient policy tools are urgently needed to overcome current barriers, and stimulate large-scale recycling of wood ash for long-term sustainable forest fuel utilisation.

## 1. Introduction

Sweden uses a particularly large proportion of bioenergy (33% in 2016), mainly for heating [1]. Almost half of all heating is delivered through district heating (DH) systems [2]. Forest fuels dominate the bioenergy used for heat, and the use of logging residues, consisting mostly of tops and branches, recovered after final felling, is increasing. In line with the political goal of a biobased economy, logging residues have the potential to satisfy a substantial part of the demand for bioenergy in Sweden, which is projected to increase over the coming decades [3]. This expansion has been promoted by various economic incentives such as a carbon dioxide tax on fossil fuels (introduced in 1991) and green certificates for renewable electricity production (introduced in 2003).

A prerequisite for the long-term, sustainable increased use of logging residues in the biobased economy is closing the material loop by recycling the wood ash from incineration to the forest, to avoid reduced forest productivity [4,5]. Apart from containing essential nutrients, such as phosphorus (P), magnesium (Mg), potassium (K) and calcium (Ca), wood ash has a significant liming effect, and is thus particularly important in preventing forest soil acidification. In accord with the findings of previous and ongoing research (see e.g. Ref. [6–9]), the Swedish Forest Agency (*Skogsstyrelsen*) has long recommended wood ash recycling after logging residue out-take as an integral part of sustainable forest management [10]. However, the availability of wood ash with suitable quality is currently low, and logging residues are removed from larger areas than are compensated for with wood ash recycling [4].

In parallel with the goals of a biobased economy, the political goal of the circular economy drives an increase in resource recirculation, through, for example, enhanced energy recovery from biological residues and waste streams [11]. Contamination poses a serious problem in achieving this goal [12]. Contaminants in waste wood added in the use phase include lead (Pb), arsenic (As), zinc (Zn) and copper (Cu) [13,14], which prevent it from being recycled, and waste wood is classified as solid recovered fuel, the landfilling of which is prohibited in the EU [15,16]. For this reason, most waste wood in Sweden is used for energy recovery in DH systems, connected to both dedicated waste incineration plants and biobased plants. The waste wood is source-separated from the

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other combustible waste streams and sorted according to quality; the hazardous waste wood fraction containing high levels of toxic compounds is sent to dedicated waste incineration plants, and the remaining fraction is considered clean enough from toxic compounds to be used together with forest fuels in co-incineration plants [17]. Consequently, in contrast to the ash from forest fuels, ash from unsorted waste wood is classified as toxic waste, and there is no goal of including it in the material loop by wood ash recycling back to the forest [18].

In the complex situation of how to include waste wood in biobased circular economy, the DH operator dimension remains unexplored. Previous studies of wood ash recycling have focused on ecological consequences, logistical management, public authority guidelines, etc. (see e.g. Ref. [19–21]), but so far not on the practical business perspective of DH operators. Today, factors such as the use of renewable feedstock, supply reliability and competitive pricing, promote the use of mixtures of solid biofuels at DH plants, for example, co-incineration of waste wood and forest fuels [22]. However, contamination of the forest fuel ash through this co-incineration practice is risking the material recycling loop. Thus, DH operator's choice to co-incineration can affect the ability to increase recycling of ash from forest fuels. This potential barrier to a biobased and circular economy has been overlooked in political decision-making. As mentioned, Sweden is at the forefront in converting its heating system to district heating, and using biofuels to replace fossil energy carriers in the development of a biobased economy, and has also come furthest in using waste wood in the development of a circular economy. Therefore, the experiences from the current situation in Sweden can be of great importance for countries with comparable conditions, as incentives for developing sustainable forest management and circular bio-economies are designed and implemented, and can lead to similar future situations.

This study was divided into three parts. Firstly, we identified the contribution of contaminants from waste wood in fly- and bottom ash from co-incineration by performing a case study of a typical DH plant in Sweden. We then quantified the extent of co-incineration of waste wood and forest fuels and wood ash recycling to forests in the Swedish DH sector, and finally identified and evaluated possible measures and strategies for DH operators to increase the amount of recyclable wood ash to forests.

## 2. Methodology and data collection

The first part of this study consisted of a case study of a typical large-scale DH plant, located in southern Sweden, where various wood fuels, including logging residues and waste wood, are incinerated, and there is currently no recycling of wood ash. The second part involved a general assessment of the DH sector in Sweden, in order to quantify the overall mix of biomass fuels utilised, the degree of co-incineration, and methods of wood ash management. The third part entailed a review of existing ash management technologies and measures that could be implemented at both the DH plant in the case study and by Swedish DH operators in general, to increase the amount of recyclable wood ash to the forest.

The case study was carried out on the DH plant at Örtofta, near the city of Lund, in southern Sweden. It is operated by the energy company Kraftringen Energi AB, which is jointly owned by four municipalities (Lund, Eslöv, Hörby and Lomma). Key personnel at the Örtofta DH plant and at Kraftringen Energi AB were identified and interviewed to collect information on the planning process and operation of the plant, including the fuels used, the combustion system, flue gas treatment, ash management, economic prerequisites, regulations and permits, strategical considerations, etc. Quantitative experimental data on nutrients (Ca, Mg, P and K) and contaminants (As, boron (B), cadmium (Cd), chromium (Cr), Cu, mercury (Hg), nickel (Ni), Pb, vanadium (V) and Zn) in the wood fuels and ash were obtained by collecting and analysing samples during a full heat load period, when waste wood (representing 57% as lower heating value (LHV) of wet biomass of added wood), and forest fuels (bark, sawdust, logging residues) were co-incinerated. The results were compared to limits recommended by the Swedish Forest Agency for wood ash recycling [10]. The contributions of nutrients and contaminants from forest fuels and waste wood are presented. A detailed description of the experimental study has been presented by Pettersson and Björnsson [23].

The general assessment of the Swedish DH sector and its current use of biomass fuels (logging residues, waste wood, etc.) and the management of wood ash (landfilling, use in construction materials, forest recycling, etc.) is based on data and information obtained from official statistics, a literature review including scientific and grey literature, and interviews with key actors.

The assessment of potential ash management technologies and measures aimed at increasing the amount of recyclable wood ash, including drivers and barriers for such recycling, is based on a broad literature review and interviews with key actors. Relevant information was compiled stepwise in order to identify and evaluate possible measures that DH operators could implement themselves, i.e. ash treatment options and pre-emptive measures to avoid unrecyclable ash, and to identify political drivers for the promotion or discouragement of such measures. The findings from this compilation were then evaluated together with the results obtained from the case study and general assessment of the Swedish DH sector.

## 3. Case study of the DH plant at Örtofta

The DH plant at Örtofta is a large-scale combined heat and power (CHP) plant, annually delivering 550 GWh of district heating, and 220 GWh of electrical power to the grid. The boiler is a circulating fluidised bed using sand as the heat carrier, co-incinerating a mixture of waste wood and forest fuels [24]. There are several reasons for this choice of fuel: diversification to ensure continuous production; minimization of production costs while meeting environmental requirements (waste wood is cheaper to buy, but the use of forest fuels requires less expensive installations for flue gas cleaning); and minimization of fuel transport distances. The fuel mixture (wet wt.%) used in 2018 consisted of 39% waste wood, 25% bark, 16% sawdust, 10% logging residues and 10% peat. Incineration resulted in 1700 and 2100 t of fly ash and bottom ash, respectively. The fly ash is classified as toxic waste, and is disposed of by landfilling, while bottom ash is used as sealing material at old landfills.

Fig. 1 shows the concentrations of contaminants in the samples of fly ash relative to the limits recommended by the Swedish Forest Agency [10]. Neither the fly ash nor the bottom ash fulfilled the requirements stated in the current guidelines for wood ash recycling to forests. Both the nutrient and contaminant concentrations are higher in the fly ash fraction than in the bottom ash fraction. The bottom ash contains a high amount of bed sand and too low concentrations of nutrients to be used for recycling, while the fly ash has nutrient concentrations that would make it suitable for recycling to the forest if it were not for the high concentrations of contaminants from waste wood.

The concentrations of the contaminants As, Pb, Cu, Cr and Zn in the fly ash greatly exceeded the recommended limits. High concentrations of these contaminants have been reported previously in waste wood [13, 14,25].

Fig. 2 shows the contents of the above contaminants and of the nutrients per GWh of added fuel (concentration multiplied by mass flow per unit energy during the sampling period) to visualise the contribution of each fuel, and the distribution of the elements between the two ash streams. At the time of the study (March 2018), waste wood constituted 57% of the energy in the added fuel (LHV wet fuel) and forest fuels 43%. Only contaminants for which the concentration in the fly ash or bottom ash did not meet the recommended limits are included in this figure.

As was showed Fig. 1, five contaminants were too abundant in the fly ash for wood ash to be recycled to the forest (whilst two were very close their benchmark concentrations, and therefore not further problematised in this study). Most of these elements originate from the waste wood, as can be seen in Fig. 2. Most nutrients originate from forest fuels,

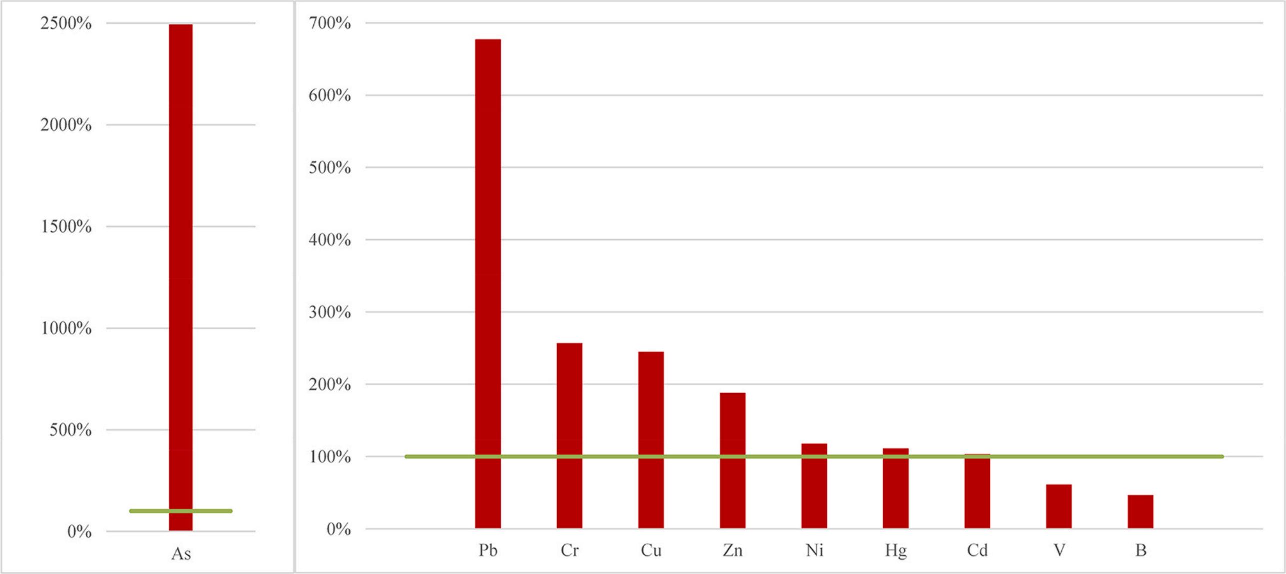

**Fig. 1.** Contaminants found in the fly ash from Örtofta CHP. The columns represent a five day average concentration (1 sample per day, each consisting of a mixture of 10 fly ash samples, ranging over 8 h), sampled during a high load production period (20180228-0304). Concentrations are given relative to the recommended limits for wood ash recycling to the forest (green line) [10]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

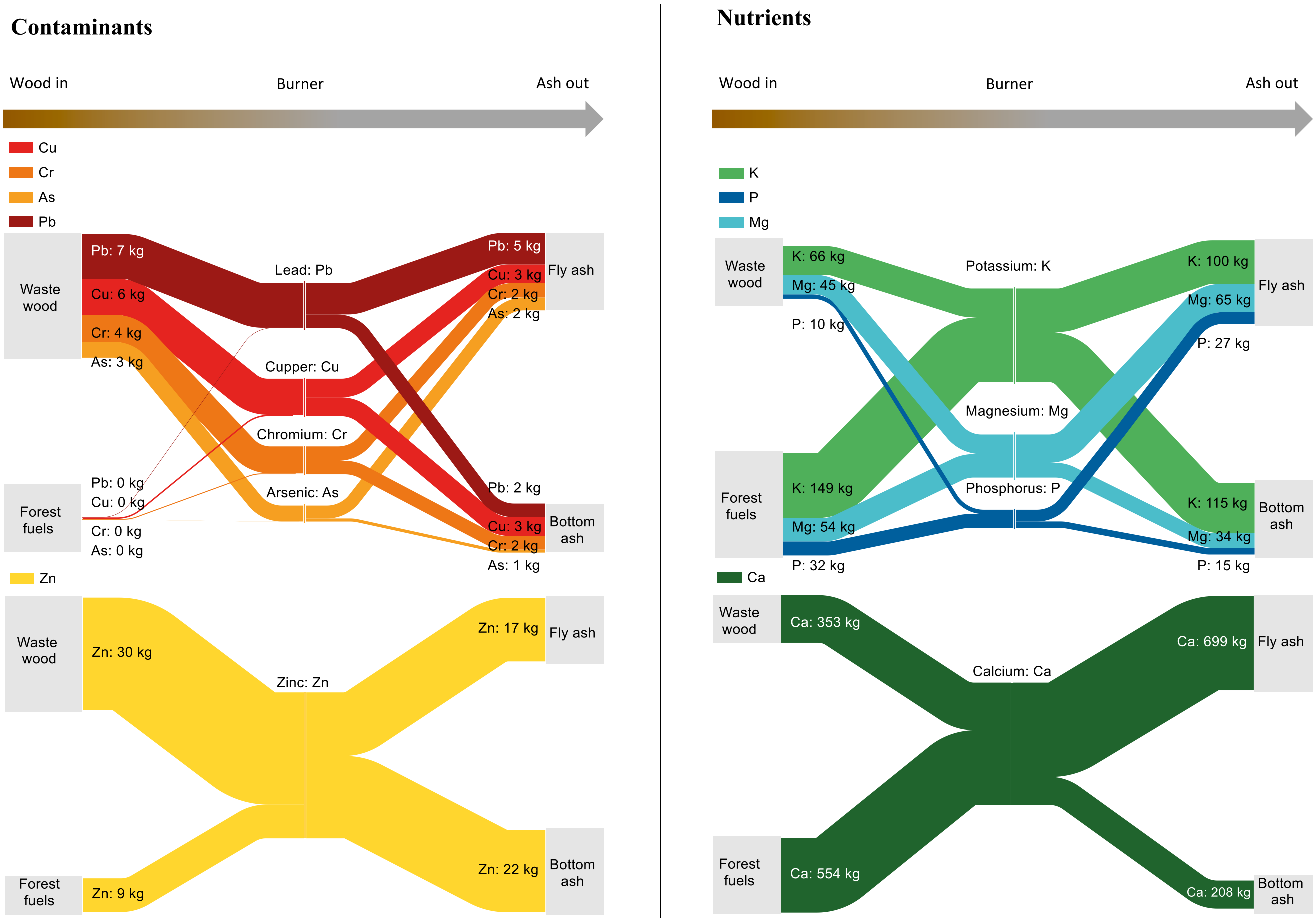

**Fig. 2.** Amounts (kg/GWh added fuel) of contaminants that exceeded the recommended limits (Pb, Cu, Cr, As and Zn), and the nutrients K, Mg, P and Ca.

and the nutrient contribution from waste wood is low in relation to the share in the fuel mixture (57%). The majority of the nutrients (with the exception of K) are found in the fly ash, but also most of contaminants.

The results of the case study show that, during the period of the study, the addition of waste wood results in ash contamination. This contamination makes the fly ash unsuitable for recycling to the forest and unusable for closing the material loop for the nutrients originating from forest fuels. The bottom ash is less toxic than the fly ash, but also has a lower value concerning nutrient content, mainly due to its high amount of inert bed sand.

## 4. Wood fuel use and wood ash management in the Swedish DH sector

The use of waste wood and forest fuels (bark, logging residues, sawdust and low-quality stem wood) in the DH sector in Sweden was surveyed to assess how common the practice of co-incineration is. The end-use of wood ash in Sweden was also investigated. As detailed national data were unavailable on individual DH plants or ash management, the incidence of co-incineration and the fate of the wood ash had to be estimated by combining official sources of data on both solid biofuel and DH supply and tariffs, installed capacity on the DH system level, ash production on the sector level, and statistics on the use of wood ash by forest owners, compiled by the Swedish Forest Agency.

The annual supply of heat in the Swedish DH sector amounts to approximately 68 TWh per year (2017), where 38 TWh (56%) is based on biomass feedstock. Most biomass-based heat is produced in CHP plants, and together they supply an additional 8 TWh of electricity per year to the grid [26]. The average price of logging residues delivered to the Swedish DH sector since 2016 is 180–190 SEK/MWh (average exchange rate in 2019: 1 € = 10.53 SEK [27]), while the price of waste wood ranged between 75 and 90 SEK/MWh (Fig. 3) [28]. The considerable difference in price between logging residues and waste wood is the main reason for the recent increase in the use of waste wood. This increase is also displayed in Fig. 3, where the share of waste wood has increased from 31% to 39% since 2013, while the aggregated energy supply from logging residues and waste wood has remained almost unchanged [29,30].

Since the statistics indicate continued removal of logging residues for energy generation (Fig. 3), the need for wood ash recycling to forests will likely remain. The parallel increase in the use of waste wood for energy purposes indicates its continued use in the national fuel mix in the future. Hence the problem of insufficient production of wood ash suitable for compensating logging residue out-take will probably continue.

The data available do not contain the level of detail required to estimate the precise proportion of forest fuel that is co-incinerated with waste wood. Therefore, this information was obtained indirectly by investigation of individual DH systems (made up by one or several DH plants) using both waste wood and forest fuels. The data used were extracted from yearly energy usage reported by the Swedish DH grid owners which was 28 TWh biomass fuel supply for heat production in 2017 [29]. This includes the supply to both small and large production facilities, but not on an individual DH plant level. It does not include systems supplied by industrial residual heat from biomass, or small supplies of biomass used internally in industries and other facilities for heat production.

Of these 28 TWh of biomass fuels used for DH production, waste wood was found to constitute about 20%, logging residues around 30%, and the remainder was forest fuels containing a mixture of stem wood chips, bark, sawdust and other[1] biomass fuels. It was also found that 20% of the total forest fuel supply is used in DH systems using both waste wood and forest fuels, possibly by co-incineration. Table 1 gives data for the ten largest Swedish DH systems with a combined annual use of >70 GWh forest fuels and >60 GWh waste wood, thereby most relevant for this study and selected to be investigated deeper. The selection was based on characteristics found in the statistics: Of the total forest fuel supply to the DH systems potentially using co-incineration, 90% was supplied to DH systems individually using 70 GWh or more, while 85% total waste wood was supplied to DH systems individually using 60 GWh or more. The Örtofta DH plant in the case study is the main supplying plant in DH system No.5.

Analysis of the ten systems listed in Table 1 indicates that co-incineration plants are usually larger, and located in the south of the country and in coastal areas with access to waste wood, which means that large quantities of ash from forest fuels could be contaminated by waste wood. Another finding was that owners of large DH systems, such as Nos. 1 and 2, are planning to increase the share of waste wood. This is in line with the projected 20–30% increase in Swedish waste wood demand by 2023; two thirds of the increase are estimated to be co-incinerated with forest fuels, both in new plants and by replacing a share of the forest fuel feedstock in current plants [17].

Considering the amount of wood ash produced in Sweden each year, there is a serious lack of reliable data. The total amount of wood ash generated in 2012 was estimated to be approximately 286 kton [31]; 255 kton from solid biomass fuels (including firewood for domestic use and additive residues from the incineration process, e.g. bed sand). The amount of wood ash that could theoretically have been recycled if it had not been contaminated was estimated to be roughly 190 kton, based on an ash content of 2% in wood [32] and the forest fuel production in 2017 [30]. Bed sand etc. will in reality add to this weight, bringing the estimate closer to the wood ash production of 2012.

There is also a lack of reliable data on the amount of wood ash recycled to the forest today. In 2012, only approximately 17% of the wood ash was recycled to the forest [31]. The rest was mainly used as construction material for covering landfills or disposed of in landfills. Only a small proportion of ashes are used for other construction purposes in Sweden, such as road stabilisation and cement [33]. In 2016, the Swedish Forest Agency estimated that the amount of wood ash recycled to forests in Sweden was 39 kton [34]. Compared to the estimated production of wood ash in 2017, this indicates a continued low share of recycled wood ash (around 20%). This amount of recycled wood ash also includes ash from the paper and pulp industry, making the amount from the DH sector even lower. The forest production area from which logging residues were removed around 2016, was estimated to be approximately 66 000 ha (a 3-year average). The amount of recycled ash recommended by the Swedish Forest Agency is 3 ton ash per ha [10], which results in a requirement of 200 kton of ash at the current logging residue out-take rate. This shows that the recycling of wood ash to forests to offset the environmental impact of logging residue out-take is not a functioning mechanism. The increase in the contamination of forest fuel ash from co-incineration with waste wood, driven by bioenergy and resource circulation incentives, is adding to the problem.

The small wood ash recycling market is characterised by practical barriers leading to high initial costs for the actors involved, for example, the low number of companies that can carry out wood ash recycling, high equipment and transportation costs, inadequate business models, and ineffective administration [35,36]. However, it is expected that these barriers will be reduced as the market evolves. There are indications that the market may be functional for operators using uncontaminated wood fuels. For example, the forest-fuelled CHP plant outside Växjö in southern Sweden (VEAB), which is of a similar size to that at Örtofta, recycles their fly ash to forests through an entrepreneur [37].

## 5. Possible measures for DH operators to increase recyclable wood ash to the forest

DH operators use co-incineration due to economic, technical,

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[1] Not including refined (e.g. pellets), or non-solid biofuels.

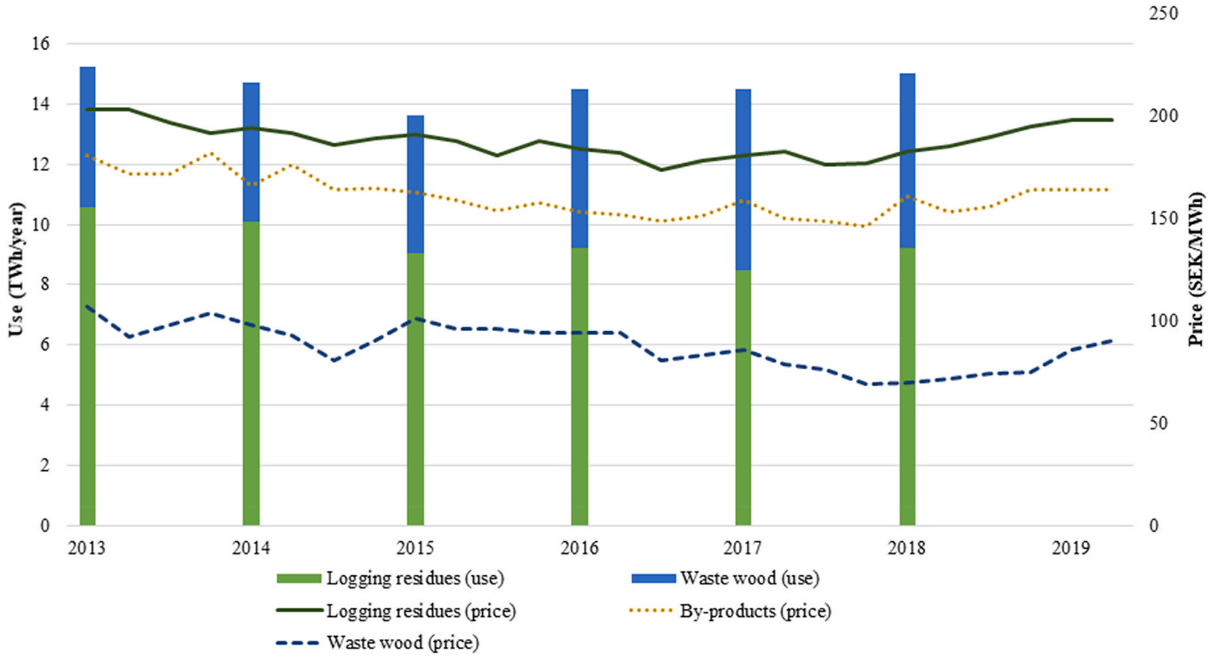

**Fig. 3.** Left axis: Use of logging residues and waste wood for energy purposes in Sweden (TWh/year) [28,29]. Right axis: National average price of logging residues, by-products from forest industries (e.g. sawdust, bark) and waste wood (SEK/MWh) delivered to DH plants in Sweden [27].

**Table 1**
The ten Swedish district heating systems[a] with the largest supply of both waste wood and forest fuels for heat production 2017 (GWh) [28].

| District heating system | Waste wood | Forest fuels[b]* | *of which is logging residues |
|---|---|---|---|
| No. 1 | 321 | 1356 | 1324 |
| No. 2 | 118 | 334 | 92 |
| No. 3 | 65 | 304 | 22 |
| No. 4 | 67 | 287 | 11 |
| No. 5 | 181 | 196 | 42[c] |
| No. 6 | 70 | 179 | 14 |
| No. 7 | 65 | 142 | 29 |
| No. 8 | 339 | 130 | 5 |
| No. 9 | 279 | 105 | 2 |
| No. 10 | 70 | 69 | 31 |

[a] The DH systems have been anonymised, according to an agreement with DH owners.

[b] Including logging residues, sawdust, bark, stem wood chips and other biomass fuels.

[c] Information from Kraftringen Energi AB [30].

regulatory, and other factors. The aim of this part of the study was to identify and evaluate possible measures and strategies to increase the amount of recyclable wood ash to the forest. Possible measures were identified by focusing on the possibilities of DH operators to influence the fuel supply chain, operational measures at the plant, and adapting the management of the ash produced. In addition, political drivers and barriers for the implementation of possible measures were evaluated.

### *5.1. Upstream: Replacing waste wood in the fuel mix*

One obvious measure is to exclude contaminated waste wood in the fuel mix of an individual DH plant, and replace it with forest fuels such as logging residues, bark and sawdust, so that the wood ash could be recycled to forests. The equipment requirements are similar [38], and are assumed to be interchangeable from a technical point of view. Fuel replacement would be unproblematic at the Örtofta plant from a technical point of view as a forest fuel mix would meet the fuel quality requirements of the combustion equipment.

The main barrier to the exclusion of waste wood in the fuel mix, however, is economic, as waste wood is cheaper than logging residues and by-products from forest industries (Fig. 3). The DH market is subject to strong competition from, for example, alternative heating technologies such as individual heat pumps, so the scope for increased DH tariffs is limited. Industrial by-products and waste wood are subject to other supply restrictions than logging residue, as they dependant on other markets, which influence the DH operators' choice of fuel mix.

Using the Örtofta DH plant case study as an example, and assuming average Swedish wood fuel prices (Fig. 3), the average cost of heating using the fuel mix during the heating season 2018/2019 (fuel purchase of 616 GWh and a use of 47% waste wood) would be 130 SEK/MWh. Replacing the waste wood used at Örtofta with forest industry by-products (Alternative 1), would increase the average fuel cost by 23–45 SEK/MWh. Replacing it with logging residues (Alternative 2), would instead increase the cost by 37–59 SEK/MWh. This would correspond to an increase in the annual fuel cost of 12–28 MSEK in Alternative 1 or 23–36 MSEK in Alternative 2. For comparison, this is equivalent to 2–5% of the total revenue from district heating for Kraftringen Energi AB in 2018 [39]. Under current DH market conditions, excluding waste wood would risk making the Örtofta DH plant uncompetitive [40].

The costs of handling fly ash and bottom ash at the Örtofta DH plant are currently 1100 SEK/ton and 330 SEK/ton, respectively. The cost of disposing of the fly ash at a landfill for hazardous waste in Langöya, Norway amounted to 2.1 MSEK in 2018, while the cost of management of the bottom ash by local actors was 1.2 MSEK. The cost of ash disposal is equivalent to only about 5–10% of the estimated increase in fuel cost if waste wood were to be replaced by forest fuel, so this would not be an economically viable option. Furthermore, the recycling of wood ash to forests will probably lead to increased costs for the DH operator.

### *5.2. Operational measure: Separate incineration of fuel fractions*

One potential operational measure could be to incinerate forest fuels and waste wood separately at different times of the year. This would lead to ash suitable for forest recycling during part of the year, and the production of less hazardous ash that has to be landfilled. The equipment requirements for incinerating logging residues and forest industry by-products are similar [38], and were assumed to be interchangeable from a technical point of view in this study. Separate incineration of waste wood and logging residues has been investigated in a previous experimental study [41]. The results showed that contaminants from the waste wood remained in the system during the 11-day trial period, contaminating the ash from the incineration of logging residues, and making it unsuitable for forest recycling. The separate incineration of different fuel streams during the year has also been investigated in waste incineration plants, and it was concluded that a lack of knowledge on the effects of different waste streams on the plant construction greatly increased the risk of equipment failure [42]. For example, it is technically possible to operate the fluidised bed incinerator at the Örtofta DH plant periodically using only forest fuels, but the walls are not constructed to withstand and absorb the rapid increase in thermal generation when incinerating only waste wood, which has a low moist content. This could result in lower heat absorption efficiency, and at worst, damage to the boiler [40].

A CHP plant is planned and designed based on a range of technical and economic factors already at an early stage, and these determine its particular operation boundaries, such as fuel properties. The lock-in effects created by design factors can make it difficult to change the plant to periodical operation with different fuels once it is built.

### 5.3. *Downstream: After-treatment of the ash*

This section presents the results of a review of the technological prospects of recovering nutrients and chemical compounds from ash after co-incineration of waste wood and forest fuels. Technologies for the treatment of ash are under development (e.g. thermal process technologies), but most forms of treatment still mainly aim at stabilisation and solidification the ash for disposal or utilisation, rather than material recovery [43,44]. Only a limited number of studies have been performed on bottom ash treatment [45–48], focusing mainly on reducing the use of fresh sand and not chemical compound recovery. All the technologies discussed below focus on fly ash treatment.

Some separation technologies suitable for ash products are available on an commercial scale, e.g. the FLUWA and FLUREC processes, which provide acid leaching extraction and the recovery of Zn, Pb, Cu and Cd, and the Stena Recycling A/S HALOSEP® method, which removes chlorine [49], but the residues after treatment cannot be used for ash recycling in forests. Using commercial scrap-metal recovery processes would be uneconomical due to the low metal concentrations in wood ash [44]. Research and development in nutrient recovery is mostly focused on P recovery from the ash resulting from the incineration of sewage sludge [50]. The technology has not been implemented in any sewage treatment plant in Sweden [51]. The purpose of this process is to recover P from contaminated ash not approved as an agricultural fertiliser. The P content is significantly lower in wood ash compared with sewage sludge ash, and the process cannot be directly applied to produce recyclable wood ash to ensure long-term, sustainable forest production [23]. So-called wet ash treatment methods (generally washing and leaching for the separation and concentration of toxic compounds), are not feasible for the treatment of wood ash that is to be recycled in forests since the nutrient K would also be leached out [44]. It can therefore be concluded that commercial ash treatment processes are not suitable for producing recyclable wood ash, where the aim is to both recycle essential nutrients and to get a liming effect to prevent forest soil acidification.

Due to the heterogeneous nature of fly ash, many different kinds of separation methods have been developed on laboratory scale [43] aimed at treating fly ash with a specific composition to remove particular contaminants [52], usually Zn, Pb, Cd, Cu and other volatile heavy metals, as well as some rare-earth metals [43]. Notably, Zn, Pb, Cd and Cu are among the important contaminants in the Örtofta DH fly ash (Fig. 1), however, it would be difficult to scale up these material recovery technologies due to economic and energy considerations [49]. Furthermore, the aim of these processes is metal recovery, rather than removing contaminants to enable nutrient recycling. Also, having to implement a combination of multiple separation processes would probably increase the total cost of treatment [53]. However, the cost of ash treatment should be considered on a systemic level [43]. For example, the cost of multiple separation processes could be covered by selling valuable metals (e.g. Ni, Cu and Zn). The recovery of materials is considered one of the most credible solutions for managing fly ash in the future [49]. Several attempts have been made to develop feasible methods, driven partly by cleaner ash, but mainly by the desire to recover high-value metals [54]. The largest bio-fuelled CHP plant in the Nordic countries uses a forest fuel mix, and its owners are currently applying for an environmental permit to start co-incineration with waste wood. Element recovery is proposed to remove contaminants from the ash [55], signalling confidence in emerging commercial ash management techniques. In conclusion, fly ash treatment technologies able to produce recyclable ash through the removal of contaminants, driven by their value as recovered metals, are not yet commercially available, but there are societal driving forces for their development.

### 5.4. *Political drivers influencing wood ash recycling*

Waste management regulations in the EU, such as the Circular Economy Action Plan, which includes legislative proposals discouraging landfilling [56], and the 2018 EU Directive on diverting waste from landfills [57], may have an effect on wood ash recycling. A ban on landfilling wood ash would prevent DH operators from producing non-recyclable ash by co-incineration. As co-incineration is one way of keeping bioenergy DH tariffs down, regulations banning ash landfilling could have a negative impact on the EU's goal of increasing the use of renewable energy, as some DH operators would not have the economic or technical means to change their DH production and still be competitive. A specific EU framework for the management of ash has therefore been suggested [19]. The Circular Economy Action plan also presents the Commission's intention to promote the use of bio-nutrients through waste-based fertilisers, partly by updating the EU Fertiliser Directive. However, this is a work in progress [58], and the practical implications for DH operators remain unclear. In the EU's waste-to-energy strategy communication, recovering fertilisers in connection with anaerobic digestion is mentioned, but there is no mention of fertiliser recovery in connection with the incineration of waste wood [11].

IEA Bioenergy (The International Energy Agency's Technology Collaboration Programme on bioenergy) states that Sweden is the only country to have national regulations and a policy specifically for wood ash recycling to forests [21]. They recommend other countries to use Sweden's regulatory framework to increase the use of ash in forestry. However, the "regulation" referred to is the voluntary recommendation of the Swedish Forest Agency, which in the survey of wood ash management in the Swedish DH sector (Section 4) was found to be a non-functioning mechanism to offset the environmental impact of logging residue out-take. Furthermore, forest fuels have been shown to contain levels of contaminants exceeding the recommended limits in the current guidelines (e.g. Ni and Cd in sawdust, and Ni in logging residues [23]). It can therefore be questioned whether these limits actually reflect the elements content removed with logging residues. Updated mass flow assessments of contaminants and nutrients in various wood fuels and related wood ashes might therefore be needed in future revisions of the guidelines for wood ash recycling.

In addition, the environmental permit, issued by the authority as part of the DH operators' design and planning process for wood-based DH production, can influence the choice of ash management. This permit stipulates the maximum allowed emissions and effluents from the actual DH plant (based on the Swedish Environmental Code (*Miljöbalken (1998:808)*)). However, recycling of ash from logging residue use is a recommendation, not a demand in current environmental permits for

DH production, and there are no specific rulings regarding recycling to forests as an ash management strategy for DH operators. In the absence of viable commercial ash treatment processes, such a demand on DH operators would lead to higher DH production costs, due to the need to use forest fuels only, or investments in boiler and flue gas treatment that allow for periodic separate incineration of waste wood and forest fuels. The investment in incineration plants for waste wood only, if this was the only option for energy recovery from contaminated fractions in the circular economy, could prove unattractive since the amount of available feedstock is dependent on recovery rates in other markets (e.g. construction demolition), meaning very little supply control [59]. Consequently, the benefit of utilising waste wood for energy recovery could be lost, and thus its demand as a separate waste stream.

Thus, while relevant visions and action plans exist on different governance levels, there is currently no specific comprehensive political tool that stimulates DH operators to increase the amount of recyclable wood ash to the forest.

## 6. Discussion

The potential environmental conflict in a combined biobased and circular economy, in the form of reduced opportunities for wood ash recycling to forests following the co-incineration of wood fuels, has been studied. A case study was performed to obtain a detailed understanding of the origin and amounts of contaminants when incinerating waste wood together with forest fuels. The results showed that, provided it was not contaminated, the ash from the incineration of forest fuels alone would be attractive for forest recycling due to its high levels of nutrients. The waste wood was found to be the source of the contaminants making the ash from co-incineration unsuitable for recycling. Co-incineration at the plant studied resulted in such high levels of contaminants that the ash was classified as hazardous, and had to be deposited in landfills. This is probably the case for a large number of Swedish co-incineration plants with similar conditions, although the heterogeneous nature of wood fuels, and waste wood in particular, would give different results regarding the type and amounts of contaminants.

To obtain a better understanding of the extent of contamination of forest fuels ash, the co-incineration with waste wood in the Swedish DH sector was quantified. The results indicated that co-incineration plants are usually large CHP plants (and thus large ash producers) located in the southern and costal parts of the country, with easy access to waste wood and high heat and power demands. There is no regulatory barrier for DH operators to produce contaminated ash, as landfilling it is legal (and often a cost competitive ash management strategy). Furthermore, there are advantages in spreading the risk of fuel cost variations and improving supply security by using a mixture of fuels, making co-incineration of the cheaper waste wood and the abundant forest fuels attractive to DH operators. Thus, co-incineration with waste wood is currently an attractive DH production set-up in Sweden, leading to an unwanted, large-scale contamination of the forest fuel ash produced in the Swedish DH sector.

The kinds of wood fuels used by DH operators in the future will depend on several factors. For example, it has been predicted that the demand for waste wood will increase not only in Sweden, but also in the countries from which Sweden imports waste wood [60]. A potential supply shortage may increase the price of waste wood, making forest fuels more competitive. Recession in the forest industries will also lead to a decrease in the supply of by-products, making it more important to ensure a high supply of logging residues [60]. In conclusion, there is reason to believe that co-incineration will continue in both existing and future plants in the Swedish DH system. The consequences of volatility in the biofuels market on the continuous demand for logging residues further advocate improved and expanded wood ash recycling systems.

The theoretical estimate of the amount of ash resulting from wood fuel incineration in Sweden matches the amount required for recycling to forests according to the Swedish Forest Agency. However, the amount of wood ash actually recycled to forest areas from which logging residues have been recovered has only been about 20% of the recommended amount over the past years. The remainder of the wood ash is landfilled or used in construction material. Thus, measures are needed to increase the proportion of wood ash recycled to logging residue recovery areas, in order to ensure long-term sustainable forest production. Continued or increasing use of co-incineration exacerbates the problem.

There is a lack of reliable data on both the amount of wood ash recycled and the areas from which logging residues are removed. A similar lack of data has also been noted in other countries with similar bioenergy use [21], suggesting that this type of survey may be problematic. Furthermore, no precise statistics were available on the fuel demand for co-incineration plants using waste wood and forest fuels, and the amount of contaminated forest fuel ash produced had to be estimated. This lack of reliable data further underlines the lack of attention paid to this type of ash production and current non-sustainable ash management strategies.

Measures that DH operators can implement to increase the amount of recyclable wood ash were identified and evaluated. Improving the quality of the ash by using only untreated wood fuel is technically feasible, but is associated with higher costs to the DH operator. Apart from cost, availability and supply security differ between exchangeable fuels. Furthermore, the current cost of ash handling is only a small fraction of the potential increase in fuel cost. For a plant such as that at Örtofta, periodically changing the type of fuel is not viable due to high refitting costs and the uncertain effect on the ash quality. However, this approach should be studied further. Each individual operator must investigate how this would affect their overall revenue, and compare it to other current and future costs, such as those for plant refitting and ash management. The results also show that treatment technologies intended to remove contaminants from wood ash to make it suitable for recycling to forests, or to recover nutrients for recycling, are not commercially available today for DH operators. Current developments within ash treatment technologies are mainly focused on the recovery of specific high-value metals, or the solidification of materials in the ash for disposal. This indicates that future measures should focus on researching downstream treatment technologies that are implementable in practice and evaluating their associated costs.

There are no comprehensive policy tools today that stimulate recycling of wood ash to the forest. Support schemes for bioenergy and waste-to-energy conversion have overlooked the fact that co-incineration may lead to contamination of forest fuel ash, hindering long-term forest production goals. Without a clear political incentive, DH operators will continue to employ co-incineration and find other ways to manage their ash, rather than recycling to the forest. However, any future incentive should not be in conflict with the important role of DH operators in an economic and environmentally sustainable fossil-free heat production system. Future strategies may include new and developed regulations for waste wood management, promoting the use of separate combustion units fuelled by either forest fuels or source-separated waste wood. However, the impact of such regulations needs to be analysed further. Based on the results of this study, one solution may be new regulatory tools that require both new and eventually existing DH operators using logging residues to recycle wood ash, thereby ensuring sustainable utilisation of forest fuels, and avoiding the compromise of long-term forest production goals. Furthermore, this will probably lead to the development of an immature wood ash recycling market, thereby helping to overcome current practical barriers, such as logistics, and reduce the cost of wood ash recycling.

## 7. Conclusions

The findings of this study show that co-incineration of forest fuels and waste wood leads to contaminated wood ash, and that co-incineration is common in the Swedish DH sector. Contamination prevents the recycling of wood ash from the DH sector, and thus long-term forest production goals, as long as logging residues are harvested. The many types of barriers identified, technical, economic and political, show that DH operators have no, or little, incentive to increase the amount of recyclable wood fuel ash, while being encouraged to increase their utilisation of waste wood fuels. This indicates that policies promoting a circular economy, on both a national and international level, should stimulate wood ash recycling to close the material loop of forest soil nutrients. This would be in line with the political goal of a biobased economy, without risking the long-term environmentally and economically sustainable increase in the utilisation of logging residues for bioenergy production. The first step in such a development is to clearly visualise this overlooked challenge, and disseminate this knowledge to policy makers.

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