Sensitivity Analysis of the Climate Effect of Using Pyrochar Biofuel for Heat and Electricity Generation

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Abstract: This study aims to quantify the climate change impact of pyrochar production from pulp and paper mill sludge and the subsequent utilisation in combined heat and power (CHP) plants for co-generation of heat and electricity using the environmental life cycle assessment (E-LCA) method. In the Pyrochar Scenario, in which the sludge is pyrolyzed into pyrochar, the authors have assumed that pyrochar would replace coal. In the Reference Scenario, sludge is incinerated with a subsequent low rate of energy recovery. A comprehensive sensitivity analysis was performed to determine the conditions in which the sludge pyrochar would offer the greatest climate-effect benefits. The parameters selected for the said analysis are the form of pyrochar (pellet or powder), fuels replaced by it in the CHP plant (solid waste and peat vis-à-vis coal), and the utilisation of the pyrochar fuel in another European country (Germany and Spain vis-à-vis Sweden). The results of this E-LCA clearly show that using pyrochar as a biofuel in CHP plants delivered a considerable reduction in greenhouse gas (GHG) emissions (−1.87 tonne CO\textsubscript{2}-eq per 2.8 tonne dry sludge). Contribution analysis reveals that the process accounting for the biggest share of the reduction is the pyrochar combustion (a negative contribution of 76%), which results in a displacement of coal-based fuels. The authors conclude that the utilisation of pyrochar in firing units would provide the highest reduction in GHG emissions, while recommending a comprehensive economic analysis in addition to climate effect assessment, before making a decision regarding the introduction of sludge pyrochar to the energy sector.

Keywords: CHP plant; E-LCA; energy recovery; pulp and paper mill sludge; pyrolysis

1. Introduction

Currently, climate change is one of the most pressing environmental issues and thereby it has become the basis for many policies and legislations formulated and implemented globally. It is an indisputable fact that greenhouse gas (GHG) emissions from anthropogenic activities contribute significantly to global warming, which is a precursor to the undesirable effects of climate change [1]. One of the well-entrenched, tried-tested-trusted strategies to reduce GHG emissions is to use biofuels in combined heat and power (CHP) plants, as replacements for fossil fuels [2].

The primary energy input to a CHP can range from fossil fuels (including peat) to biofuels to solid wastes. The solid wastes could be biotic (of biological origin, or organic in nature, and therefore renewable) or sourced from petroleum (essentially biotic but renewable only over several human lifetimes). While the dependence on fossil fuels has to be decreased as much as possible to mitigate global warming and the resultant climate change effects, biofuels and bio-wastes are highly preferred to coal [3]. When it comes to the use of solid wastes—paper and plastics essentially—the waste management hierarchy in which ‘Recovery of Energy’ surely is preferable to ‘Landfilling’, is respected. However, energy recovery is still environmentally inferior to the first three options in the hierarchy referred to—‘Reduce’, ‘Reuse’ and ‘Recycle’. While many European countries still use fossil
fuels in their CHPs, Sweden has gone a notch or two higher by discontinuing coal and also importing wastes from countries like Norway and the UK. Persson and Münster [4] have, however, labelled continental exports and imports of wastes as being ‘untenable’, presumably implying that in a longer time perspective, this practice should be discontinued. If such imports have to be avoided, and fossil fuels need to be phased out of the fuel-mixes adopted by Swedish CHPs—the latter being a target set by the Swedish government for year 2040 to generate electricity by 100% renewable sources [5], it is extremely imperative to seek locally-sourced, climate-neutral substitutes.

Biochar produced from local organic wastes can be looked upon as a source of bioenergy for CHP plants. In the Swedish forestry sector, solid wastes like pulp and paper mill sludge are incinerated, and the energy recovery therefrom is low. The production of biochar, for use as fuel, is expected to improve the degree of energy recovery from these waste streams.

Pyrochar is a type of biochar, produced by resorting to pyrolysis—a thermal process for biomass carbonization in an oxygen-limited environment. Its heating value is high enough to be considered for energy generation applications [6,7]. In addition, if the production and utilisation processes can also contribute to truncating the environmental footprint vis-à-vis the fuels in vogue, pyrochar (or biochar in general) is in a position to entrench itself permanently in the energy sector of Sweden.

At the time of writing, one has access to a vast body of literature on environmental life-cycle analysis (E-LCA) in the waste management sector. Pyrochar furnishes a wide range of advantages for a range of applications—high carbon content, high cation exchange capacity, stable structure with a high surface-area-to-volume ratio. It finds potential applications as soil amendment, heat and electricity generation as a biofuel, and absorbent in wastewater treatment plants [8–10]. Environmentally and economically, while its use as soil amendment has been accepted widely [11–13], its utilisation as a source of energy has not been studied in sufficient detail. In an E-LCA study, Peter et al. [14], compared various options for pyrolysis char application. They found that co-combustion of pyrochar with fossil coal in a power plant is the best alternative, when seen from the perspective of truncation of the environmental footprint. They also showed in their study that soil application of biochar is environmentally superior to direct incineration of the biomass, only for the global warming environmental impact category. This benefit, evidently is thanks to the potential for sequestering the carbon in the pyrochar by admixture with the soil.

As far as the soil amendment application of pyrochar is concerned, Mohammadi et al. [15] compared different thermal treatments—combustion, pyrolysis and hydrothermal carbonization (HTC)—for their environmental footprints, vis-à-vis a reference case for which sludge landfilling was considered. They showed that while all alternatives were indeed preferable to landfilling, the pyrolysis process provided the greatest reduction in GHG emissions (−1.43 tonne CO$_2$ per tonne dry matter in sludge). The importance and relevance of such an analysis to objectively identify and quantify life-cycle environmental impacts, must never be underestimated.

The aim of this study is to calculate and compare the climate change impact of two scenarios for the management of pulp and paper mill sludge using the E-LCA methodology. One of these is the Pyrochar Scenario in which pyrochar is produced from sludge for combustion in energy plants to generate both heat and electricity. Ash from the combusted pyrochar is assumed to be mixed with soil. The other scenario is the Reference Scenario in which the sludge is incinerated with low energy recovery and the ash from the combusted sludge is assumed to be landfilled. A comprehensive sensitivity analysis is conducted on different parameters to investigate the uncertainties related to the findings of the E-LCA analysis.
2. Materials and Methods

2.1. Goal and Scope Definition

In this analysis, an E-LCA was conducted to quantify the climate impact of the pyrochar systems where pyrochar is produced from pulp and paper mill sludge. The sludge pyrochar was assumed to be treated as biofuel for cogeneration of heat and electricity in CHP plants, vis-à-vis the incineration of the sludge in pulp and paper mills.

In an environmental systems analysis, it is important to have a comparative approach to produce meaningful results, and for this purpose, the analyst defines a so-called “functional unit”. The functional unit used in E-LCA studies of pyrochar production systems varies from mass of feedstock [16,17], to mass of generated pyrochar [18] or carbon content in produced pyrochar [19] or to have multi-functional units [20]. In this work, the authors have selected the amount of dry matter sludge required to produce 1 tonne (t) of pyrochar (which is around 2.8 t dry sludge), as the functional unit (FU).

2.2. System Boundaries and Scenarios

The first process in the system, the ‘cradle’, is sludge collection from a pulp and paper mill. This is followed by all subsequent processes and transformations, leading up to the end-use of pyrochar as fuel in CHP plants, and the resultant ash in agricultural and forest ecosystems as a soil amendment (Figure 1). While utilisation of energy is dissipative, the use of the ash can be looked upon as the ‘grave’ of the process chain. Two scenarios were considered in this analysis and they are described in detail below.

Figure 1. The system boundaries representing the E-LCA study for using pyrochar in CHP plants including the sensitivity analysis parameters. The dashed lines represent avoided processes. The acronyms WWTP, CHP and SA represent wastewater treatment, combined heat and power and sensitivity analysis respectively.

2.2.1. Reference Scenario (RS)

The Reference Scenario represents the conventional use of sludge and conventional fuel sources. In this scenario, the sludge is dewatered and then delivered to an incineration plant which recovers energy at a conversion efficiency of 35% [21]. The residual ash from sludge incineration is transported to landfill sites.
2.2.2. Pyrochar Scenario (PS)

In this scenario, the dewatered sludge is dried to 15% moisture content (MC) and converted into pyrochar in a large-scale pyrolysis unit with an annual processing capacity of around 4700 t dry feedstock. The pyrolysis gases released during the carbonization process are captured to recover heat for drying the incoming dewatered sludge and also for district heating purposes. This heat recovery supplants the conventional fuels in vogue. The pyrochar is then transported to CHP plants where it is combusted for cogeneration, the energy outputs being fed into the national power grid and the district heating networks.

The paper and pulp mills on the upstream (the ‘cradle’ from which the sludge is collected) are assumed to be in the south-central province of Värmland in Sweden, and the pyrochar production and heat-and-power generation are also assumed to take place in the same province.

2.3. Material Flow Analysis

Material flow analysis (MFA) is indispensable for a systematic assessment of the flows and stocks of materials/substances within the designed scenarios as well as to provide the basis for the subsequent E-LCA study. MFA, in other words, is a necessary precursor to E-LCA. In this assessment, the sludge (on dry mass basis) and the other input materials were taken into account in all the processes, and the flows of carbon (in the sludge) and energy in the entire life cycle of Pyrochar Scenario, were quantified (refer Section 2.4).

The amounts and forms of inflows to a process in an MFA may be different from those of the output flows, especially in transformation processes like pyrolysis or incineration. The partitioning of a material in a process, and its transfer into another process is calculated and presented, with the aid of so-called transfer coefficients (TC) (refer Equation (1)). The TC can link the ratio between inflow ($X_{input}$) and outflow ($X_{output}$) or the efficiency of conversion of input primary energy to output final-use energy, as shown in Equation (2).

$$X_{output} = X_{input} \times TC$$

$$E_{output} = E_{input} \times efficiency$$

2.4. Inventory Analysis

In order to set up the inventory, data were gathered mostly from relevant published literatures and the ecoinvent 3.1 databases [22], for Swedish conditions and for the other European countries (for the sensitivity analyses), Section 2.6 provides more details.

Since the analysis consists of a scenario (pyrochar application in CHP plants) which is not in vogue currently, the selection of data sources becomes very critical for the reliability of the end-results of the analysis. In this study, data from the published literature have been chosen based on similar studies conducted in Sweden or in other Nordic countries.

The chemical properties of the sludge, directed to the pyrolysis process, and the pyrochar were gathered from Rasa et al. [23] and Ahlroth et al. [24] and presented in Supplementary Information (SI), Table S1.

Fiber sludge and biosludge from pulp and paper mills (in a 1:1 ratio) as feedstock, and the average value of the elemental and energy contents of these two sludges and the pyrochar produced from each of them, were considered for this analysis.

The ash content of the sludge is 12% of dry matter (DM). The sludge from pulp and paper mills contains high percentages of carbon (46%), oxygen (29%) and some hydrogen (6%) which explains its high heating value. The initial MC of the sludge at the site is found to be 98%. The collected sludge is then dewatered by gravity thickening, centrifuging and pressure-filtering to 65% MC.

The electricity required and polymers consumed for dewatering were accounted as 323 kWh and 26 kg per 2.8 t dry sludge (Suh and Rousseaux [25]). Incineration and pyrolysis require 630 kWh and 45 kWh per functional unit (FU) respectively [15,16,26].
In the drying process, the MC of the sludge must be decreased to 15% to make it amenable to the pyrolysis process. The energy required to evaporate the moisture is calculated based on its heat of vaporization (2.5 MJ per kg of water). Within the pyrolysis unit, the MC of feedstock is reduced further to 2%, using the heat recovered from the pyrolysis gases [26]. The remaining heat (10.2 GJ) is assumed to replace district heating fuels in the Värmland province.

The BigChar 2200 pyrolysis plant, which is a continuous operation system, has been assumed to be constructed in the Värmland area to convert sludge to pyrochar. The facility is assumed to have used 7.7 t of steel as the main construction material, and is estimated to have an operation rate of 90% over a 10-year lifetime. The unit has a vertical rotary heart reactor, which works at temperatures ranging from 500 to 900 °C (the optimal temperature being 720 °C). The unit needs 8.1 kg diesel for its start-up and 15 kW of electricity per hour to operate continuously. More information about the pyrolysis plant is available in [27]. Flue gas treatment is recommended in both the systems to control the emissions of pollutants like mercury into the atmosphere. The input materials for this treatment are calcium chloride, sodium persulfate, sodium hydroxide, ammonia, hydrochloric acid, sulphuric acid and sodium chloride according to Larsen et al. [16].

The heat and electricity generation from the CHP plant is dependent on the calorific value of the pyrochar and the energy conversion efficiency of the plant. A heat efficiency of 57.8% and an electricity-generation efficiency of 8.1% were considered, based on a case study of a CHP plant in Karlskoga in the Värmland province of Sweden [3]. The electricity use in the CHP plant was assumed to be 5% of the generated output.

The heat generated contributes to the avoidance of the use of district heating fuels by 9 GJ per FU. However, a 10% loss was assumed for a transmission distance of 5 km [26].

By applying ash to amend soils in fields and forests, it may safely be assumed that the use of some chemical fertilizers (sources of nitrogen, phosphorus, potassium and micronutrients, inter alia) can be avoided. About 1520 g of nitrogen and 200 g of phosphorus can be thus added, per functional unit [15]. The avoided fertilizer was accounted for, based on the plant availability of the nutrients from applied ash (18–35%) relative to the 65–70% plant availability from mineral fertilizer [28].

A reasonable transport distance of 10 km from the pyrolysis unit to the CHP plant for transporting pyrochar, and of 50 km from the CHP plant to forest and/or agricultural soil for transporting ash were assumed in this E-LCA. The assumptions and life cycle inventory for the two scenarios are summarized in Table 1.

| Table 1. Inventory data for pyrochar production and its application in CHP plants (expressed per 2.8 t dry sludge, FU). |
|-----------------------------------------------|-------------|----------------|
| Inputs                                       | Unit | Amount |
| Electricity—Dewatering                        | kWh  | 323    | [15]         |
| Electricity—Incineration                      | kWh  | 630    | [16]         |
| Electricity—Pyrolysis                         | kWh  | 45     | [15]         |
| Start-up burner fuel                          | kg   | 8      | Diesel (Pyrolysis) |
| Electricity WW T                              | kWh  | 40     | [29]         |
| Polymer                                      | kg   | 26     | Dewatering [25] |
Table 1. Cont.

| Unit Amount | Comments/Source |
|-------------|----------------|
| Calcium chloride kg 1.86 | Fly ash treatment in both incineration and pyrolysis [16] |
| Sodium persulfate kg 1.83 | |
| Sodium hydroxide kg 94.3 | |
| Ammonia kg 4.63 | |
| Hydrochloric acid kg 5.71 | |
| Sulphuric acid kg 3.43 | |
| Sodium chloride kg 1.69 | |
| Ammonium chloride kg 4.04 | Phosphorus precipitation agent, WWT [29] |
| Ammonia kg 1.62 | CHP [16] |

**Outputs**

| Unit Amount | Comments |
|-------------|----------|
| Pyrochar kg 1000 | Heat to district heating from Pyrolysis [30] |
| Heat GJ 16 | |

**Emissions**

| Unit Amount | Comments |
|-------------|----------|
| Methane, CH$_4$ kg 0.26 | |
| N$_2$O g 10 | WWT [29] |
| CO$_2$ kg 11 | |

**Energy Substitution through Use of Pyrochar in CHP Plants**

| Unit Amount | Comments |
|-------------|----------|
| Heat GJ 9 | To district network from CHP [3] |
| Electricity kWh 333 | To power network from CHP [3] |
| Ash kg 330 | By-product of combustion [24] |

**Avoided**

| Unit Amount | Comments |
|-------------|----------|
| Combustion Coal kg 3500 | |
| N$_2$O g 1 | Soil application [32] |
| NO$_3$ g 2 | |
| Ammonium NH$_4$ + g 122 | Soil application [33] |
| N fertilizer g 1520 | Soil application [28] |
| P fertilizer g 200 | |

**Other assumptions**

| Unit Amount | Comments |
|-------------|----------|
| Pyrochar yield % 35 | [34] |
| Transport distance km 60 | 10 km to CHP, 50 km to soil site |
| Energy recovery from Incineration % 35 | [21] |
| Combustion efficiency % 86.5 | |
| Electricity conversion efficiency % 8.1 | [3] |
| Heat conversion efficiency % 57.8 | |
| Efficiency—heat transport % 90 | [26] |

2.5. Assessment

E-LCA is performed according to the methodology described in the ISO 14040:2006 standards using the SimaPro 8.0.4 software [35] and inventory data including the Ecoinvent 3.1. database [36]. The method of IPCC 2013 GWP with a time horizon of 100 years is used in this assessment to calculate the climate change impact of the systems with the unit of kg CO$_2$-eq.

2.6. Sensitivity Analysis

A comprehensive sensitivity analysis was conducted to determine the effect of parameters on the results of climate change impact from the Pyrochar Scenario. The selected pa-
Parameters for the sensitivity analysis encompass the processes of incineration and pyrolysis and the CHP plant, as well as the impact assessment method, time horizon and transport.

2.6.1. Incineration

The only parameter studied in the incineration process is the amount of energy recovery from the incineration of sludge. About 35% of total energy content of the sludge is assumed to be recovered as heat. This rate as the baseline (BL) value is increased/decreased by ±20% and ±30%.

2.6.2. Pyrolysis

By changing the temperature at which the sludge is pyrolyzed, the quantities of pyrolysis gases and pyrochar can be changed. For this sensitivity analysis, the temperature is increased from 540 °C to 900 °C, with 720 °C being considered as the BL value. These temperatures are selected as the studied pyrolysis plant can appropriately work with different feedstocks in the temperature range between 500 to 900 °C. Another parameter is the physical form of the pyrochar—powder or pellets. In order to pelletize pyrochar, lignin is considered to be used as a binder during the pelletization process. This can also influence the heating value of the product. A medium-size pelleting machine with a product mass flow of 40 kg/h and electricity requirement of 0.05 kWh is assumed in this analysis to pelletize pyrochar [37], with a material loss factor of 5%.

2.6.3. CHP Process

In the BL, the combustion fuel replaced in the CHP plant is coal. In the sensitivity analysis, this parameter is changed to solid municipal waste and peat in two separate analyses, to test how these changes influence the climate change impact of the system. Likewise, the sensitivity of the results to changes in the heat and electricity generation efficiencies has also been tested by increasing/decreasing the same by ±20% and ±30%.

2.6.4. Location of CHP Plant (Geographical Sensitivity)

The location of the CHP plant may also play a key role in the performance of the system. Spain and Germany are considered as potential export destinations for the pyrochar produced in Sweden. The transport distances, the avoided hard coal combustion (coal is a common fuel in the Spanish and German CHP plants), the power generation mixes of the two countries, and the types of district heating fuels used are accounted for.

The transport distance to CHP plant and to forest and/or agricultural sites for land application of ash is another parameter which was tested in the sensitivity analysis, and increased/decreased by ±20% and ±30%.

2.6.5. Impact Assessment Method

The scope of the calculations changes when the impact assessment methods used are changed. The authors, in this paper, have considered, in addition to the IPCC (BL method), IMPACT 2002+ and ReCiPe Midpoint.

3. Results and Discussion

3.1. Material and Energy Flow Analysis

Figure 2a demonstrates material and carbon flows in the pyrochar system from the ‘cradle’—sludge collection—to the ‘grave’—soil application of the ash. The avoided process of combustion coal (the dashed line in Figure 1) indicates that it is carbon that is being replaced by pyrochar in the CHP plant, and for this study, it is 0.5 t carbon/FU. The quantity of biosludge decreases as one moves downstream in the system, owing to dewatering and drying (which decreases the MC). The carbon content also shows a similar trend. This is because carbon is stored in the pyrochar and some of it is released to the atmosphere mainly as carbon dioxide during combustion. Additionally, there are losses associated with the handling and transport processes. Referring to the MFA diagram, one notes that a
substantial part of the carbon in the sludge is not transferred to the pyrochar. Now, such a transfer is very necessary if one wishes to sequester carbon in the soil by using the pyrochar as a soil amendment. The carbon that is not bound in pyrochar leaves the pyrolysis process to a small extent as methane, but mostly as part of the pyrolysis gas, which then finds use in drying within the pyrolysis plant and also for district heating. The detailed transfer coefficients to processes are presented in SI, Table S2.

3.2. Climate Change Impact

On comparing the two scenarios (RS—Reference Scenario and PS—Pyrochar Scenario) for managing sludge, it is seen that the former does not bring about any abatement, while the latter provides a net reduction in GHG emissions. The positive values refer to the emissions of GHGs into the atmosphere and negative values represent the avoided emissions. The total net GHG emissions for RS is 323 kg CO$_2$-eq per 2.8 t dry sludge (FU) and for PS is $-1.87$ t CO$_2$-eq per FU (Figure 3).
The results of pyrochar scenario is in line with the other findings of the published literature. Mohammadi et al. [26] concluded that the production of hydrochar from sludge (a type of biochar produced by hydrothermal carbonization—HTC), and subsequent combustion in a CHP plant reduced the GHG emissions significantly (−0.723 t CO₂ eq. per t dry sludge), vis-à-vis sludge incineration. These results also conform to the ones arrived at by Berge et al. [38], a research paper in which an E-LCA approach was used to assess the environmental impacts linked to the HTC of food wastes and the combustion of the produced hydrochar for energy generation. Their results illustrated a saving of 0.018 kg CO₂ eq. per kg food waste with 68% MC is achievable when the electricity production from hydrochar is used to offset coal-based fuel sources.

3.3. Contribution Analysis

The results of contribution analysis for the both scenarios are presented in Figure 4. For the RS, the largest contributor to the total GHG emissions (in CO₂-eq.) is the incineration process (62%). The requirement of electricity to run the unit (which includes that for the mandatory flue gas cleaning process) accounted for a big share of this contribution.
In the PS, the avoided use of conventional fuel elements, courtesy the generation of heat and electricity from pyrochar in the CHP units is the dominant contributor to the abatement of GHG emissions (a negative contribution of 76%). The contribution of the dewatering process in the PS is 5%, while the corresponding value in the RS is over 30%. Dewatering is the second largest contributor in the RS due to its reliance on electricity use. Berge et al. [38] have reported that the hydrochar production from food waste, followed by its combustion in CHP units, provided conspicuous benefits (−99%) in the reduction of the GHG footprint of food waste management. Those authors assumed that the hydrochar is used in coal-fired power plants, with the purpose of avoiding the use of coal. Mohammadi et al. [24] have also concluded likewise, in favour of hydrochar as a source of energy.

3.4. Sensitivity Analysis

Figure 5 shows that varying temperature (between 540–900 °C) in the pyrolysis process had an effect on the abatement of GHG emissions from the pyrochar system through the changes in processes of the energy generated in the CHP plant to replace conventionally-generated heat and electricity, and the soil application of ash. The variations in the pyrolysis temperature influence the amount of pyrochar and gases generated during the process [39]. At lower temperatures in the specified range, the pyrochar yield is higher, indicating a greater degree of conversion of sludges to pyrochar and thereby lower production of pyrolysis gas. As the temperature increases, the share of pyrolysis gas in the output increases. The results of the sensitivity analysis demonstrated that the contribution of the pyrolysis process to abatement in GHG emissions increases with a rise in temperature. This is explained by a rise in the production of pyrolysis gas, which can be used as a source of heat to substitute greater amounts of district heating fuels (coal or municipal solid waste) (Figure 2b).

Figure 5. Sensitivity of the GHG emissions abatement of Pyrochar Scenario to the pyrolysis temperature 540 °C, 720 °C (baseline-BL) and 900 °C.

However, a rise in pyrolysis temperature to 900 °C, implies a drop in the production of pyrochar by 5%, and thereby in the amount of fuel supplied to the CHP unit. It follows that energy output from the unit will also decrease. The mass of bottom ash to be handled also reduces by 12% in this instance, decreasing the amount of synthetic fertilisers that can be replaced.

A decrease in the temperature to 540 °C results in an enhancement in pyrochar yield by 14%. This implies higher heat and electricity generation in the CHP unit, and consequently a rise in the GHG abatement potential by 19%. Total systemic changes in the climate effect are 10% and 5% for a pyrolysis temperature of 540 °C and 900 °C respectively.
What should be remembered here is that this applies to a specific industrial pyrolysis plant. It is recommended to consider different pyrolysis techniques, such as slow and fast pyrolysis, as well as different sizes of plants—small, medium and large—with different operating temperatures in studies in the future.

Pyrochar can be pelletized in order to improve the ease of handling, transport and storage. By resorting to pelletizing, further abatement of GHG emissions is possible. This would be 13% more than the baseline scenario, which is equivalent to 2110 kg CO₂ (Figure 6). The pelletizing process has a very small GHG footprint (less than 1%). During the process, lignin which has a calorific value of 25 MJ/kg, was assumed to be added as a binder [40]. Hence, the combustion of pelletized pyrochar in the CHP plant generates more heat and electricity as compared to the combustion of powdered pyrochar.

![Figure 6. Sensitivity of the climate impact of Pyrochar Scenario to changing the pyrochar form from powder to pellets.](image)

In addition to environmental benefits, the economic parameters would be one of the major contributors to adoption of new bioenergy technologies [41,42]. The economic aspect of pyrochar implementation as biofuel, in neither powder nor pelleted form, has not been well documented. Pelletizing pyrochar considerably depends on initial feedstocks, pyrolysis conditions and densification techniques [43], however, including this process might increase the production cost by 0.11 USD/kg [44] in the entire supply chain of pyrochar pellet.

In RS, lignin is burned in the paper and pulp mills without energy recovery. However, the lignin can very well be considered for use in other applications—in vehicles, construction, coatings, plastics and pharmaceuticals [45]. These applications however are outside the scope of this E-LCA study. The fabrication of the pelletizing machine is not included in the calculations, under the assumption that its contribution would be insignificant. Further studies are however called for, to investigate the advantages conferred and challenges imposed by feedstock quality, pyrolysis conditions and technologies on the potential to produce high-quality pellets.

The results of the sensitivity analysis showed that the type of district heat fuel which is displaced through the use of pyrochar in power plants, affects the LCA outcomes. In the baseline scenario, it was assumed that pyrochar substitutes the fossil fuel of coal, however, if pyrochar displaces peat and solid waste in the firing units, the total climate impact of the studied systems would be −741 and −818 kg CO₂-eq per FU, respectively. It means the GHG emissions abatement is decreased by 60% and 56% in the cases of peat and solid waste fuels (Figure 7). Mohammadi et al. [26] have confirmed that using hydrochar instead of coal reduces CO₂ emissions by a greater extent (by 0.723 kg CO₂-eq per t of sludge dry matter), as compared to replacing solids wastes with hydrochar (by 0.121 kg CO₂-eq).

The location of the CHP plant is the last parameter considered in the sensitivity analysis. By changing the CHP plant location from Sweden to Germany and Spain, the total reduction of CO₂-eq emissions declines by 3.7% and 15% respectively as seen in
In this study, the energy conversion efficiency in the CHP plant is assumed to be the same regardless of the location of the plant. However, the heating values of the coal which is replaced by the pyrochar, differs. Figure 8 clearly shows that over 1500 kg CO₂-eq per 2.8 t of dry sludge handled, can be mitigated when pyrochar is exported to Spain and Germany for energy recovery from CHP plants.

Figure 7. Sensitivity of the GHG abatement of Pyrochar Scenario to the avoided CHP plant fuel (peat and solid waste).

Figure 8. Sensitivity of the climate change effect of Pyrochar Scenario to the location of CHP plant within the EU region (Spain and Germany).

The sensitivity analysis results of on other parameters on climate effect of the Pyrochar Scenario, such as climate impact time horizon, transport distance, energy conversion efficiency in CHP plants, are illustrated in SI (Figures S1–S6).

Based on the performed sensitivity analyzes on the various parameters, the optimal condition for each parameter is presented in Table 2.
Table 2. The optimal condition for each parameter considered in the sensitivity analysis (See SI for the results of the last six items).

| Parameter                                      | Optimal Condition | Improved GHG Emissions Abatement |
|------------------------------------------------|-------------------|----------------------------------|
| Pyrolysis temperature                         | 540 °C            | 10.4%                            |
| Pyrochar form                                  | Pellet            | 13.0%                            |
| Avoided CHP plant fuel                         | Coal              | BL                               |
| CHP plant location                             | Sweden            | BL                               |
| Time horizon                                   | 20-year           | 30.2%                            |
| Rate of energy recovery in incineration process (RS \(^a\)) | 0.46%             | 5.1%                             |
| Transport distance                             | 42 km             | 0.04%                            |
| Impact assessment methods                      | IPCC              | BL                               |
| Electricity conversion efficiency in CHP plant | 10.5%             | 5.4%                             |
| Heat conversion efficiency in CHP plant        | 75.1%             | 20.4%                            |

\(^a\) Reference Scenario.

3.5. Implementation of Pyrochar Systems

In Sweden, unlike in many other countries, coal accounts for a very small percentage of the heat and power mix. Pyrochar thus is a potential candidate to be considered for the defossilisation of global energy mix, and thereby a key strategy in Sweden’s roadmap towards greening its grid completely by 2040, and reach the ambitious target of zero net GHG emissions by 2045 \([5]\). Biomass is one of the most important fuels for Swedish district heating (45% \([46]\)) and electricity production (22% \([5]\)) respectively. By upgrading pulp and paper mill sludge to high-value pyrochar-biofuel, these shares can be increased. Pyrochar, as a bio-fuel, is admittedly in an incipient stage at the time of writing, and more research is needed to entrench it as one. Previous studies have shown that the fuel quality of raw biomass can be significantly increased through the carbonization process in the production of biochar \([14,38]\). Pelletizing pyrochar contributes to easier handling and transport, and overcomes the challenges associated with the low bulk density and high dust levels of the powdered form \([47–51]\).

In this work, we calculated the climate benefits from the use of one tonne pyrochar in energy plants in either powder or pelleted form. If we simulate the implementation of pyrochar systems to large scales, e.g., in an area or the whole country of Sweden, we will observe the significant figures. For instance, the region of Värmland in Sweden, where four pulp and paper mills are located, produces around 54.1 t dry fiber sludge and biosludge each day \([52]\). If all of these sludges are converted into pyrochar for energy purposes, approximately between 32.7 to 36.1 t CO\(_2\) eq. emissions per day can be saved depending on the produced pyrochars feed CHP plants in Sweden or in another European country. These values would increase by 13% if the sludge pyrochars are pelletized before application in the firing units.

This study therefore, shows that pyrochar derived from paper and pulp mill sludge, provides considerable environmental benefits by replacing coal, solid waste and peat. Prima facie, the favourability of pyrochar may seem counter-intuitive, when compared with solid waste as a source of fuel, owing to the energy requirement of the production process. However, it must be pointed out here that reliance on solid wastes as a source of fuel for the CHP plants in Sweden, entails some imports of the same too. Besides, incineration of and energy recovery from solid wastes imposes burdens on the environment, occasioning global warming, toxicities of different types and depletion of natural resources (considering that material recycling of solid wastes would be a preferable option to incinerating them for their energy content) \([53]\). Thus, by replacing solid wastes with pyrochar and focusing on recycling the former, a progression towards a circular economy can be easily enabled. Having said that, it would be necessary in that case to focus on improving material recycling processes continually.
4. Conclusions

In this E-LCA study, the authors have been able to demonstrate that the use of paper and pulp mill sludge to produce pyrochar for subsequent use as fuel in CHP plants in Sweden, can bring about a considerable abatement of GHG emissions (~1.87 t CO$_2$-eq per 2.8 t dry sludge) vis-à-vis the conventional, in-vogue incineration of sludge with the low rate of energy recovery. It was assumed by the authors that pyrochar combustion would substitute the use of fossil-coal in the CHP units. Avoidance of coal contributed the most to the said abatement (76%), followed by the pyrolysis process (17%). The processes of transport and drying contributed the least to the GHG emissions from the Pyrochar Scenario, with the recovery of heat from the combustion of pyrolysis gases in-plant, making the contribution of the drying process almost negligible.

The results of the sensitivity analysis indicated that there are many parameters that affect the E-LCA results, and thereby it is important for decision-makers not to overlook them. The parameters of interest were the physical form of the pyrochar (powder or pellets), the alternatives replaced by the pyrochar in the firing units (solid waste, peat, coal), and the geographical location of the point-of-use of the pyrochar (Germany and Spain compared to Sweden). According to our results, if all fiber sludge and biosludge produced in Värmland area, Sweden, are converted into pyrochar to fuel the CHP plants, approximately between 32.7 to 36.1 t CO$_2$ eq. emissions per day can be mitigated depending on the location of the CHP units where they are in Sweden or in another European country.

The authors believe that this study, which is a part of a small body of literature, will motivate and inspire further research into the potential of pyrochar production and-use systems around the world. Future research may well encompass the following:

- Application of E-LCA to comparatively analyse different CHP technologies with various energy conversion efficiencies.
- This E-LCA study modelled a specific pyrolysis unit. Other E-LCAs can be applied to study other carbonization technologies like slow pyrolysis, fast pyrolysis and gasification, at different scales, factoring in the differences in the yield and quality of the pyrochar output as well as that of the pyrolysis gases which find use as a source of heat energy.
- As pelletized pyrochar clearly is preferable to the powdered form, optimisation of pelletization techniques from economic, environmental and functional perspectives will be a topic of interest for researchers.
- A thorough economic assessment of pyrochar production technologies, from cradle to end-use (including the cost savings associated with avoided processes), will be a very useful decision-making aid.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/pr9101744/s1. Table S1: Major chemical elements (% dry matter) in pulp and paper mill sludge (mixed fibre sludge and biosludge) and pyrochar [1–3], Table S2: Transfer coefficients (TC) for pyrochar application in combined heat and power plants, Figure S1: Sensitivity of climate impact of Pyrochar Scenario calculated based on time horizon of 20-, 100- (baseline-BS) and 500-year, Figure S2: Sensitivity of the GHG emissions abatement of Pyrochar Scenario to the rate of energy recovery through incineration process in Reference Scenario (the baseline value is increased/decreased by ±20% and ±30%), Figure S3: Sensitivity of the GHG emissions abatement of Pyrochar Scenario to the transport distance (the baseline value is increased/decreased by ±20% and ±30%), Figure S4: Sensitivity of the climate impact of Pyrochar Scenario to the impact assessment methods (IMPACT 2002+ and ReCiPe Midpoint), Figure S5: Sensitivity of the climate effect of Pyrochar Scenario to the electricity conversion efficiency in CHP plant (the baseline value is changed by ±20% and ±30%), Figure S6: Sensitivity of the climate change impact of Pyrochar Scenario to the heat conversion efficiency in CHP plant (the baseline value is changed by ±20% and ±30%).

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**Abbreviation**

- BL Baseline
- CHP Combined heat and power
- DM Dry matter
- DW Dewatering
- E-LCA Environmental life cycle assessment
- FU Functional unit
- GHG Greenhouse gas
- HTC Hydrothermal carbonization
- MC Moisture content
- MFA Material flow analysis
- PS Pyrochar scenario
- RS Reference scenario
- SA Sensitivity analysis
- SI Supplementary information
- TC Transfer coefficient
- WWTP Wastewater treatment plant

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