INNOVATIVE HYDROTHERMAL CARBONIZATION (HTC) PROCESS FOR A NORDIC PULP AND PAPER MILL

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ABSTRACT: The common way of handling sludge from pulp and paper (P&P) mill's wastewater treatment plant (WWTP) is combusting it at the site. Combustion is rather a way to dispose the sludge than take advantage of its energy content. This case study assesses the potential to convert the wet low-value feedstock, specifically WWTP's secondary sludge, to a more valuable bioenergy product called HTC biocoal through hydrothermal carbonization (HTC) combined with wet oxidation using C-Green's innovative OxyPower HTC technology. We assess the integration to a Nordic sulphate pulp mill as a retrofit and compare it to baseline scenario of combusting sludge in the recovery boiler. The approach contains assessment of effects of integration to pulp mill's mass and energy balance, and market, economic and environmental assessments. The results show that the retrofit has positive impacts on the pulp mill's mass and energy balance, such as reduced evaporator and recovery boiler load. Greenhouse gas emissions reduction of 77% compared to baseline scenario proved the environmental benefits of the retrofit. However, it is challenging to find an economic case for HTC biocoal production in P&P industry due to efficient sludge treatment already taking place. Furthermore, End-of-Waste status is needed before entering the markets.
Keywords: bioenergy, hydrothermal carbonization, wastewater treatment, sludge, pulp and paper industry, retrofitting

1 INTRODUCTION

Pulp and paper (P&P) sector is actively seeking ways to renew their business strategies with new bio-based products, such as energy products, chemicals and raw materials [1]. Also, more and more attention is paid on the resource efficiency and sustainability of the consumption patterns [2]. These offsets create excellent opportunities for new innovative bio-based technologies if they can be proven economically feasible and sustainable.

Although biomass accounts for 60.0% of total fuel consumption within the P&P industry [3], fossil fuels are still actively replaced with renewable alternatives especially in lime kilns [4–6]. On-site solid side streams are seen as one option to increase the renewable energy self-sufficiency [7]. Sludge is a large side stream that can be valorized [8] and anaerobic digestion is already applied at several mills [9–11].

Another option to exploit the large sludge volumes is hydrothermal carbonization (HTC), which can be applied to produce a solid biofuel, of which the name HTC biocoal is used in this case study. The product is commonly also known as hydrochar. Although the suitability of the HTC technology for industrial scale use has been proven [12] and wide variety of applications (including exploiting as biofuel) for the product has been found [13], the technology has not been used commercially in pulping industry. Today, one commercial-scale demonstration is on-going in the pulp and paper industry, at Stora Enso's Heinola fluting mill [14,15]. Thus, the applicability in the sector still requires assessing the suitable pre-conditions for exploitation.

The bioenergy retrofits studied in the BIOFIT project [16] are defined as technical measures applied to existing production plants that support bioenergy utilisation as an alternative to fossil energy. Ten concrete proposals (Case Studies) for bioenergy retrofitting at five different industry sectors are investigated in the project. This paper presents a BIOFIT pulp and paper sector Case Study, in which carbonization of pulp mill's wastewater sludge with the C-Green's innovative OxyPower HTC technology at a Nordic pulp mill for sludge disposal and production of biocoal is studied. The Case Study comprises an assessment of effects of retrofitting to pulp mill's mass and energy balances, and market, economic and environmental assessments. The suggested retrofit scenario was compared to the baseline scenario, which is the current state of the pulp mill i.e. sludge is combusted in the recovery boiler.

The novelty of this study is that several effects of integrating the combination of the HTC technology with wet oxidation to a Nordic Kraft pulp mill are addressed. Not only the effects on mass and energy balances have been assessed but also additional effects on the mill's wastewater treatment and on make-up chemicals. Furthermore, such an assessment has not been reported for the optimised C-green OxyPower technology [17] that does not need external heat and produces more degradable effluent compared to standard HTC processes.

2 STATE-OF-THE-ART OXYPOWER HTC TECHNOLOGY

Hydrothermal carbonization is a method of converting wet organic sludge such as manure, sewage sludge and biosludge from industrial WWTPs to a solid

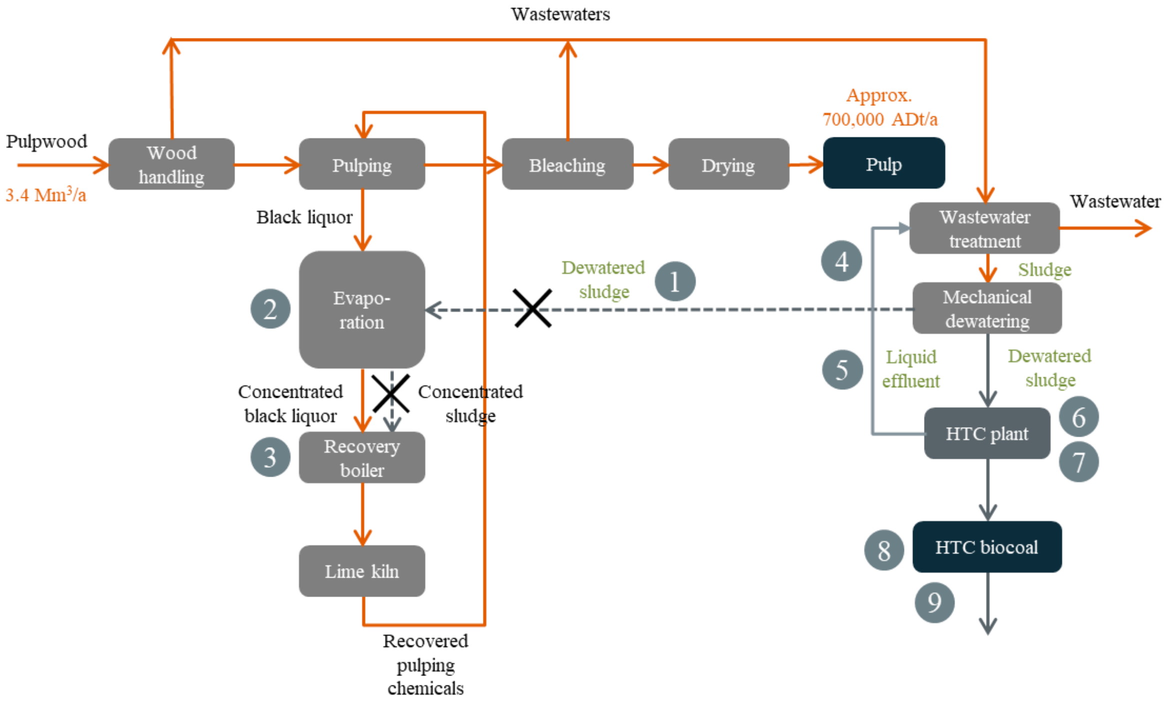

Figure 1: Baseline scenario, in which mechanically dewater sludge from the WWTP is combusted in the recovery boiler, and retrofit scenario, in which HTC biocoal is produced from the sludge through hydrothermal decarbonization. Numbers refer to the key effects of the HTC plant integration on the pulp mill process described in Section 3.2.

carbon-rich material called hydrochar or HTC biocoal. The HTC process was first described in literature by the German scientist Friedrich Bergius in 1913. Almost 100 years later HTC was implemented commercially mainly due to restrictions on waste handling in Germany and the Netherlands. The basic HTC process has two challenges; high need for external heat and COD rich process water.

C-Green`s OxyPower HTC process [17] produces all the heat needed by a combination of efficient heat recovery and wet oxidation. In the HTC reactor, sludge is converted into two separate phases: an HTC biocoal particle slurry phase and an aqueous phase, containing dissolved organic components. By treating the aqueous phase with oxygen (wet oxidation), organic substances are eliminated and heat is formed. The solid HTC biocoal produced is odorless, sterile, storable, contains over 98% of the phosphorus in the sludge and can be used as fuel for thermal production of heat and/or power or for soil improvement.

3 METHODOLOGY

In the baseline scenario, a Kraft pulp mill produces approx. 700,000 air-dried tons of pulp out of 3.4 million m^3 of pulpwood. The production leads to 4,725 tons of dry solid matter sludge production annually at the mill's WWTP. The sludge is mechanically dewatered and fed to the evaporation together with black liquor and incinerated in the recovery boiler in order to exploit its energy content.

In the retrofit scenario, the HTC process is integrated to the pulp mill to treat the secondary sludge into a HTC biocoal product instead of disposing it by incineration. The product aims to external markets as biofuel. Both the baseline and retrofit scenario are illustrated in Fig. 1. Numbers in Fig. 1 relate to Section 3.2, where the key effects of the HTC plant integration on the pulp mill process are described.

3.1 Methodology for the market assessment

For conducting the market assessment, relevant European and Finnish directives and regulations were studied. HTC biocoal characteristics, gained from the laboratory tests, were compared with legal requirements and standards. Since HTC biocoal is considered as waste, there is no market for this product established so far. Potential applications were assessed in order to find arguments for changing the status of HTC biocoal to by-product instead of waste. This would enable an End-of-Waste (EoW) status and the establishment of a market.

3.2 Methodology and assumptions for the economic assessment

The economic feasibility of the HTC plant integration was assessed in two different scenarios: 1) investment through loan (Scenario A), and 2) receiving a financial benefit called Energy Aid (30% of the total expenditure), while the remainder of the total expenditure is financed from the company's capital (Scenario B). The metrics used for the cash flow analysis are net present value (NPV), internal rate of return (IRR) and the payback period of the investment. Also, a sensitivity analysis for IRR was performed by using Investment Aid percentage, HTC biocoal product price and CAPEX as variables.

The following list describes the key effects of the HTC plant integration on the pulp mill process, which have to be considered in the economic assessment (numbers refer to Fig. 1):

1. 4,725 t/a dry matter sludge (10.4 wt-% dry solids content) is removed from evaporation and recovery boiler and led to HTC plant.
2. Energy demand for evaporation decreases

4,390 MWh/a.
3. Heat output from the recovery boiler is reduced by 20,212.5 MWh/a, which leads to lost power production of 4,800 MWh/a. The value of the lost power production is assumed to be the cost of the feedstock for the HTC process (i.e. biosludge).
4. Biogas could be produced from the liquid HTC effluent, but this option is not considered in the study.
5. HTC effluent replaces the urea needed in the pulp mill's WWTP, since the effluent contains nitrogen in the form of ammonia (1.6 g/L NH_3-N). 60 t/a of nitrogen is replaced. This is a cost saving for the mill.
6. HTC plant consumes 1,260 MWh/a power, e.g. for oxygen production.
7. Cooling water flow (110 kWh/t of dry sludge) at 50-60 °C from the HTC process could be exploited, but it is assumed that it does not have any monetary value.
8. HTC biocoal absorbs sulphur and potassium, which reduces make-up NaOH consumption in the recovery cycle. This is a cost saving for the mill. Also metals are absorbed in the HTC biocoal.
9. 5,610 t/a HTC biocoal is produced (48 wt-% moisture content, 7 GJ/t wet bases LHV).

The main assumptions and input values for the economic assessment are given in Table I.

Table I: Main assumptions and input values for the economic assessment.

Input	**Value**	**Unit**
Availability	350	days/a
Secondary sludge feed	13.5 4,725	tons of dry solids/d tons of dry solids/a
Electricity price	45	€/MWh
HTC biocoal price	40	€/MWh
Urea price	200	€/t
NaOH price	400	€/t
HTC plant CAPEX	7.0	M€
HTC plant maintenance cost	0.14	M€/a
Discount rate	9	%
Interest rate	2.64	%
Project lifetime	20	a
Energy Aid	30	% of total expenditure
Baseline scenario	**Value**	**Unit**
Heat content of the sludge burned in the recovery boiler at 80% moisture content	20,212.5	MWh/a
Water evaporated (sludge assumed to be dried to 80% wt-% solids conc.)	39,526	t/a
Evaporator specific heat consumption	0.11	MWh/t water
Evaporator heat consumption	4391.8	MWh/a
Retrofit scenario	**Value**	**Unit**
Lost power production	4,800	MWh/a
Lost income from power production i.e. cost of the feedstock for HTC plant	0.2	M€/a
HTC plant power consumption	40 1,260	kWh/t sludge MWh/a
Power cost for HTC plant	0.0567	M€/a
Income from HTC biocoal	0.44	M€/a
NH_3-N in water	1.6 60.3	g/L t/a
Urea consumption	130.5	t/a
Income from savings in nitrogen	0.026	M€/a
Reduced NaOH consumption	281	t/a
Income from savings in NaOH	0.11	M€/a

Laboratory tests were performed for the secondary sludge sample (see Fig. 2) from a Nordic Kraft pulp mill to determine the HTC biocoal yield and energy content. It was concluded that 5,610 t/a HTC biocoal is produced (48 wt-% moisture content, 7 GJ/t wet bases LHV).

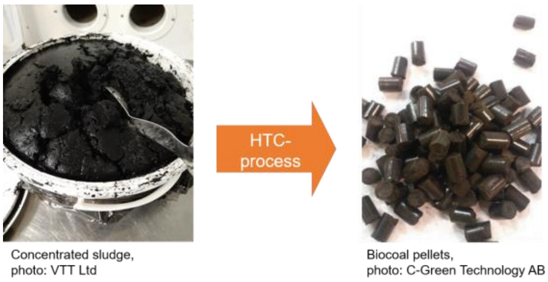

Figure 2: Concentrated secondary sludge sample (left), which is the raw material for HTC biocoal (right).

3.3 Methodology and assumptions for the environmental assessment

A simplified life cycle assessment (LCA) study based on RED II methodology was performed in order to assess the greenhouse gas (GHG) emissions of the HTC biocoal production, and, at the same time, provide a scientific basis for policy-making regarding the sustainable development of biomass fuels. LCA estimates the GHG emissions of a product, taking into account all relevant GHG processes from raw materials resources to the supply of the product services.

The simplified LCA study focusing on GHG calculation was carried out for the baseline scenario, i.e. the production and combustion process of biosludge, and the retrofit scenario, i.e. the production and combustion process of the HTC biocoal. The baseline and retrofit scenario provide the same service; thermal energy obtained from the combustion process. The system boundaries of the process chains for the GHG calculations are shown in Fig. 3 for the baseline scenario and in Fig. 4 for the retrofit scenario. In the baseline scenario, the process chain starts with co-feeding biosludge and black liquor in the evaporation plant, and ends with the exploitation of their energy content through their incineration in a recovery boiler. The only difference of the retrofit scenario is the treatment of the biosludge into HTC biocoal, instead of leading it directly to the recovery boiler of the pulp mill (incineration process). The GHG emissions of both scenarios are calculated – via RED II – using the IMPACT 2002+ methodology [18] for the simplified LCA calculations.

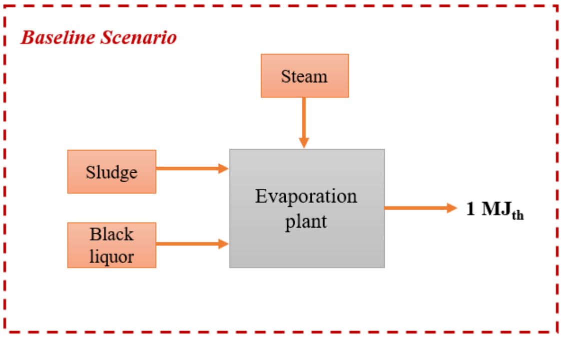

Figure 3: System boundaries of baseline scenario for GHG emissions evaluation.

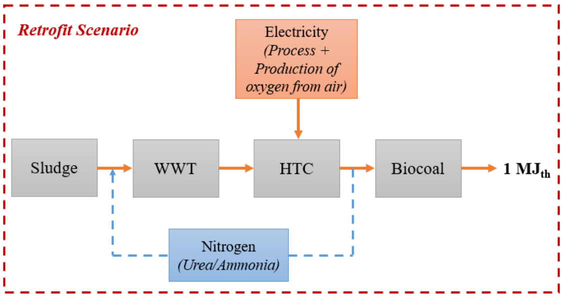

Figure 4: System boundaries of retrofit scenario for GHG emissions evaluation.

According to RED II, the functional unit set in this work, is defined as “Greenhouse gas emissions from biomass fuels (E)”, and expressed in terms of “grams of CO_2 equivalent per MJ of biomass fuel, $gCO_{2eq}/MJ_{biomass\ fuel}$”. E is evaluated with Eq. (1) [19]:

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} \quad [gCO_{2eq}/MJ_{biomass\ fuel}] \quad (1)$$

where:

e_{ec} = emissions from the extraction or cultivation of raw materials;

e_l = annualized emissions from carbon stock changes caused by land-use change;

e_p = emissions from processing;

e_{td} = emissions from transport and distribution;

e_u = emissions from the fuel in use;

e_{sca} = emission savings from soil carbon accumulation via improved agriculture management;

e_{ccs} = emission savings from carbon capture and geological storage; and

e_{ccr} = emission savings from carbon capture and replacement.

In addition to the GHG calculation, the assessment of the relevant GHG savings is mandatory for each amount of biomass fuel brought on the European market. Based on RED II, the GHG savings from substituting fossil fuels with biomass fuels are calculated as in Eq. (2) [19]:

$$Saving = \frac{EC_{F(h)} - EC_{B(h)}}{EC_{F(h)}} \quad (2)$$

where:

$EC_{B(h)}$ = total emissions from the heat produced from biocoal in [gCO_{2eq}/MJ];

$EC_{F(h)}$ = total emissions from the fossil fuel comparator for useful heat in [gCO_{2eq}/MJ]

It is worth mentioning that in RED II Directive (Annex V, part B, in paragraph 19), the fossil fuel comparator for useful heat production is estimated at 124 gCO_{2eq}/MJ_{heat}”.

4 RESULTS AND DISCUSSION

4.1 Market assessment

Since HTC biocoal is currently declared as waste, there is no market for HTC biocoal so far. Therefore, the first priority is reaching an EoW status in order to generate a market. Article 6 of the European Waste Framework Directive [20] defines criteria for an EoW status. Summarized, a certain waste material has to be used for a specific purpose and a market or demand has to exist. Additionally, the waste material has to fulfil technical requirements, meet existing legislation and it must not lead to overall adverse environmental and human health impacts.

Use as solid fuel or as soil amendment were identified as most promising applications for HTC biocoal. Further treatment of HTC biocoal could enable an application as solid fuel if the EoW status can be reached and if it complies with limit values. Decreasing moisture content to 30% and eventually pelletizing could enable e.g. co-firing at coal power plants. According to C-Green, pelletizing is possible for HTC biocoal from pulp mill sludge. Only cadmium content in HTC biocoal, deriving from wood, exceeds limit values of heavy metals in soil (defined in the Finnish Waste Act Fertilizer Regulation). However, by mixing HTC biocoal into substrate for acting as an additive in fertilizers would lower the content. The closest to the market solution for use of HTC biocoal seems to be combustion as solid fuel at the mill site, since this is explicitly excluded from the scope of Waste Framework Directive.

Producing HTC biocoal adds value to a low-value feedstock. Nutrients (e.g. phosphorus) of the feedstock can be recovered in a more flexible way compared to e.g. mono-incineration of sludge. The production causes low CO_2 emissions. Additionally, HTC biocoal has a good combustion performance (except net calorific value) and is as solid fuel ready for the market. Handling during transport and storage, especially when pelletized, is easy.

Main barrier of HTC biocoal is the declaration as waste. An EoW status is needed to add value and get the allowance to trade. Currently, also transportation needs extra permission. The low heating value limits applications. Ash and moisture content as well as heavy metal concentration are high, and limit values of current standards are exceeded.

Adding value to a waste stream is fully in line with European and national climate targets. EU supports decarbonisation of energy and steel industry, carbon pricing and circular economy. The political pressure on the steel industry could open up a market for cheap biofuels. Just a few tests at industrial scale have been done so far, however, research and demonstration is ongoing and further supported. Additionally, valorisation of waste is an alternative to land filling.

The declaration as waste prevents HTC biocoal market from emerging. This results in lacking standards and long-time research. Additionally, HTC biocoal has to compete with cheap fossil fuels and biochar, which is profiting from the huge amount of forestry residues and better soil amendment properties.

4.2 Economic assessment

For each of the two retrofitting scenarios, a cash flow analysis was carried out as outlined in the methodology. For the first scenario, hereafter referred to as Scenario A, the investment of the HTC plant is completely financed by means of a loan, whereas for the second scenario, hereafter referred to as Scenario B, a subsidy in the form of Energy Aid is anticipated and the remainder is financed from the company's capital. The reasoning behind the elaboration of these two scenarios is that there are strict limitations to be adhered in order to receive Energy Aid. At this point, it is unclear whether these limitations can be met. The economic performances of the scenarios are compared to the current state of the pulp mill.

Fig. 5 shows the cash flow of both scenarios and the base case. The sludge that is currently being combusted in the recovery boiler to produce electricity will be redirected to the HTC plant. Consequently, there is no net sales of electricity in both scenarios. This slight loss of income is offset by the much larger income from the HTC biocoal.

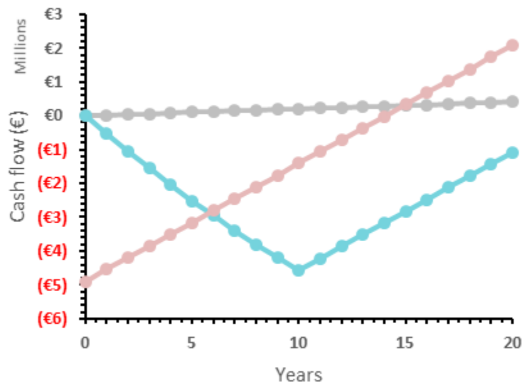

Figure 5: Cash flow diagram for the base case (grey line), Scenario A (blue line) and Scenario B (pink line).

Noticeably, Scenario A onsets a steep decline in cash flow which inverts to an increase in cash flow identical to that of Scenario B. The sole reason for this trend is that the loan cost is quite extensive and is set to be repaid after 10 years. After the 10-year mark, the operational costs and sales of both scenarios are similar. Hence, identical cash flows are observed after the 10-year mark.

Fig. 5 further reveals the economic viability of Scenario B. The cash flow of Scenario B exceeds that of the base case at year 15. To the contrary, Scenario A is perceived as economically infeasible as it shows a negative cash flow after a project period of 20 years along with the fact that it does not exceed the cash flow of the base case. Fig. 6 reinforces these findings as it shows the different economical evaluations in more detail.

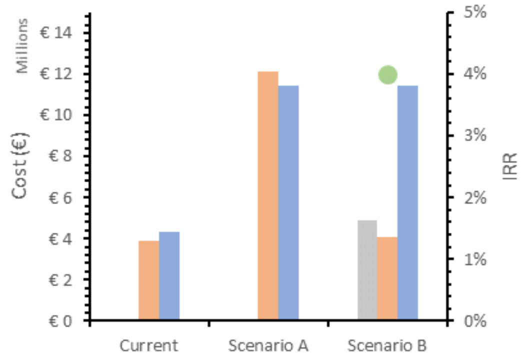

Figure 6: Economical evaluations for the different scenarios considered. Orange bar: operational cost; Blue bar: product sales; Grey bar: capital cost; Green dot: IRR.

In Fig. 6, it is quite readily observed that the product sales within Scenario A do not compensate for the operational costs, and consequently the scenario shows a negative cash flow. In contrast, the product sales within Scenario B significantly exceeds the operational cost. Supplementary to the figure is the IRR of both scenarios. Only for Scenario B, a positive IRR of 4% is observed, meaning that this scenario is economically viable. The total investment of 4.9 M€ (grey bar), which includes 30% Energy Aid, shows a payback period of approximately 14 years.

Results of the sensitivity analysis for IRR in the case of 30% Energy Aid is presented in Fig. 7. There is a positive correlation between the IRR and HTC biocoal price and Energy Aid percentage, while the correlation between IRR and CAPEX is negative. Surprisingly, changes in HTC biocoal price and Energy Aid percentage show only limited impact on the IRR.

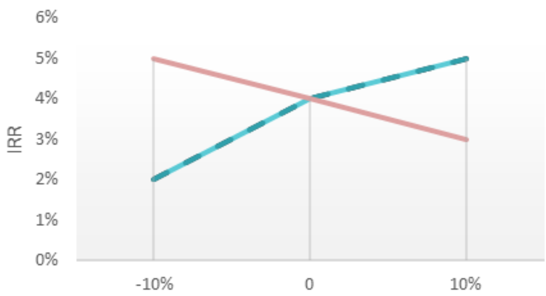

Figure 7: Sensitivity analysis for IRR with Investment Aid percentage (black dotted), HTC biocoal product price (blue) and CAPEX (light red) as variables. The variables HTC biocoal price and Energy Aid percentage show identical sensitivities and therefore overlap each other.

4.3 Environmental assessment

The GHG emissions in the retrofit scenario perform a great decrease compared to the baseline scenario, which is estimated approximately at 77%. In the baseline scenario, the estimated GHG emissions for 1 MJ of produced biosludge are 16.7 gCO_{2eq}. In case of retrofit scenario, the corresponding figure for 1 MJ of produced HTC biocoal is estimated at 2.81 gCO_{2eq}. The GHG emissions savings are estimated at 86.5% and 97.7% in case of baseline and retrofit scenario, respectively, as compared to RED II. It is evident that the retrofit scenario seems to be the most sustainable scenario in environmental terms. The high content of carbon in the mixture of sludge and black liquor in the steam process causes the adverse impact in the baseline scenario. A summary of the results of the environmental analysis is shown in Table II.

Table II: Overview of the results of the environmental assessment.

	Baseline scenario	Retrofit scenario	Unit
Total emissions	1,218	282	$tnCO_{2eq}/a$
Emissions per MJ of fuel	16.7	2.81	gCO_{2eq}/MJ
Saving according to REDII	86.5	97.7	%

5 CONCLUSION

Market assessment clearly shows that Waste Framework Directive creates a challenge for the use of HTC biocoal, since biosludge and HTC biocoal are currently declared as waste. EoW status is needed to create higher value and a market for the product. HTC biocoal as solid fuel would be ready for industrial use, but EoW status is needed. Most promising applications seem to be use as soil amendment and replacing fossil fuels in energy production.

From the technical point of view, the retrofit has several positive impacts on the pulp mill's mass and energy balance. Retrofit can for example enable increase in pulp production capacity if either evaporator or recovery boiler has been the bottleneck in the production. In addition, the HTC plant integration replaces urea consumption in the WWTP and make-up NaOH consumption in the recovery cycle, which leads to cost savings for the mill. Furthermore, HTC biocoal absorbs metals.

HTC integration leads to internal rate of return (IRR) of 4%, when a 30% Energy Aid is received. The economic assessment shows that it is challenging to find an economic case for HTC biocoal production in P&P industry in the Nordic context, as sludge can already be disposed in the recovery boiler without any gate fees. The additional revenue from the product is not enough to justify the additional investment in the treatment process. The economic feasibility could be improved if sludge would have to be transported from the site (transport cost and gate fee) before the HTC plant integration, or benefits from the increased pulp production capacity would be accounted. IRR and HTC biocoal price and Energy Aid percentage show a positive correlation, while the correlation between IRR and CAPEX is negative.

Environmental assessment shows the benefits from biocoal production achieved from the secondary sludge treatment via the HTC process. In specific, the environmental assessment proved that the retrofit scenario is a more sustainable scenario in environmental terms compared to the baseline scenario with a reduction in GHG emissions of about 77%.

In addition, urea used in the WWT process is replaced by the ammonia nitrogen in the HTC effluent, thus reducing CO_2 emissions related to its production. HTC biocoal product binds part of the biogenic carbon originating from the sludge. In the baseline scenario, all the biogenic carbon is released to atmosphere through combustion of the sludge. One challenge in the HTC process is to reduce the ash forming minerals after the WWT. The investigation of the behavior of minerals during the HTC procedure alongside their potential control by process parameters are still in the development stage.

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