BIOCHAR PRODUCTION FROM MUNICIPAL SEWAGE SLUDGE VIA PYROLYSIS

– THE CASE OF GOTLAND

Dissertation in partial fulfillment of the requirements for the degree of

BACHELOR OF SCIENCE WITH A MAJOR IN SUSTAINABLE ENERGY TRANSITION

Uppsala University
Department of Earth Sciences, Campus Gotland

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02/07/2022

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ABSTRACT

In order to keep global average temperature below 2°C it is necessary to accelerate climate change mitigation actions and reduce global greenhouse gas emissions. This can be achieved by carbon capture and storage methods such as the production of biochar. Especially its production from municipal sewage sludge could decrease emissions and disposal costs as well as act as a valuable material for different fields of application afterwards. In this quantitative study, the potential for a biochar production system was investigated for the case of the Swedish island, Gotland. Documents and grey literature were reviewed to collect the necessary information and data and experts were asked to fill in information gaps to evaluate the following: Calculate the energy and mass balance of a biochar production system from municipal sewage sludge in 2018, to find possible applications for the produced biochar by investigating the heavy metal content as well as to assess the direct carbon sequestration potential of the produced biochar. The results indicate that in 2018, 540 t of biochar could have been produced with a net heat demand of around 543 MWh_{th} and electricity consumption of 231 MWh_{el}. Heavy metal contents were found to be very high especially for copper and zinc, which means that the produced biochar would only qualify for the EBC-BasicMaterial certification class of the European Biochar Certificate. The annual carbon sequestration potential resulted in 97.2 t of carbon stored in the material or 356.4 t of CO_2 emissions saved. Further research needs to be conducted on economic factors of a biochar production system from municipal sewage sludge.

Keywords: Biochar, (Municipal) Sewage Sludge, Pyrolysis, Carbon Sequestration, Heavy Metals, Gotland

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NOMENCLATURE

Ag	Silver
amu	Atomic mass unit
Bi	Bismuth
BMSS	Biochar from municipal sewage sludge
Cd	Cadmium
CDR	Carbon dioxide removal
CO_2	Carbon dioxide
COP	Conference of the Parties
Cr	Chromium
Cu	Copper
EBC	European Biochar Certificate
g	gram
Hg	Mercury
IPCC	Intergovernmental Panel on Climate Change
K	Potassium
kg	kilogram
kW	kilowatt
kWh	kilowatt-hour
mg	milligram
MSS	Municipal sewage sludge
MWh	megawatt hour
N	Nitrogen
Ni	Nickel
P	Phosphorus
Pb	Lead
SDG	Sustainable Development Goal
Sn	Tin
t	ton
Ts	Torrsubstans = Dry Matter Content
wt%	Percentage by weight
Zn	Zinc

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1. Introduction

During the last Conference of the parties (COP) in Glasgow, the countries reaffirmed the goal from the Paris Agreement to limit the global average temperature to 2°C above pre-industrial level with attempts to limit it to 1.5°C (United Nations, n.d.a). However, according to the summary for policymakers of the latest International Panel on Climate Change (IPCC) report, global greenhouse gas emissions (GHG) in 2030 are likely to exceed 1.5°C with the implementations of the nationally determined contributions that were set at COP in Glasgow (IPCC, 2022). It is then necessary to accelerate climate change mitigation actions to limit global warming to an increase of 2°C (IPCC, 2022). The potential pathways to limit global warming in the IPCC report all imply the reduction of GHG emissions in all sectors, including the deployment of carbon dioxide removal (CDR) methods. Moreover, the IPCC assumes at least some level of negative emissions in 88 out of 90 scenarios (IEA, 2019). This clearly shows that more attention needs to be focused on the development of CDR methods and technologies. Another focus has to be directed towards the Sustainable Development Goals (SDG), implemented by the UN, which stresses the importance of solid waste management in one of their goals (United Nations, n.d.b). SDG 12 promotes sustainable consumption and production patterns, including the development of technologies to turn waste into energy (United Nations, n.d.b).

One technology that addresses the above-mentioned problems and goals is the production of biochar[1] due to its ability to sequester carbon and with that reduce greenhouse gases (Ok, et al., 2016). Moreover, it can immobilize contaminants, act as soil fertilizer component and water filter (Ok, et al., 2016), which favour plant growth (Giorcelli, Rosso and Tagiaferro, 2020). The chemical and physical compositions that make those applications possible are determined by the feedstock and the process conditions (Ok, et al., 2016).

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[1] Carbonized organic matter

1.1. Background

The following section gives background information about biochar and the biomass it is produced from, its production, applications as well as certification for biochar sold and used in Europe. Moreover, it gives information about previous research on biochar from municipal sewage sludge (BMSS) as well as the treatment of it on Gotland.

1.1.1. Input Biomass

The type of feedstock is one factor that determines the quality of the biochar as an end-product (Giorcelli, Rosso and Tagiaferro, 2020). One possible feedstock biomass is municipal sewage sludge (MSS) which is a non-lignocellulosic[2] biomass that is obtained as a by-product from municipal wastewater treatment (Li and Jiang, 2017). Every MSS has different elemental compositions but usually contains nutrients like nitrogen (N), phosphorus (P) and potassium (K) which are needed for plant growth (Li and Jiang, 2017). Other components like heavy metals and pathogens[3] on the other hand can pose a threat to the ecological environment, as they can be dissolved in water systems which can lead to water pollution and even end up in food (Li and Jiang, 2017). Moreover, MSS releases CO_2 as it decomposes in the soil (Ok, et al., 2016) if used as landfill or in agriculture. Nevertheless, the three main uses for MSS are incineration[4], soil amendment[5] and landfill (Li and Jiang, 2017). MSS as feedstock for pyrolysis is classified as wet biomass, as its water/moisture content is higher than 30% (Kwon, Lee and Sarmah, 2019). This requires a pre-drying process before being processed in a pyrolysis reactor, which leads to a reduction of the economic efficiency due to the energy intensity of the drying process (Kwon, Lee and Sarmah, 2019). On the other hand, the production of biochar from MSS does not compete with the biochar produced from energy or food crops (Kwon, Lee and

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[2] An animal-based biomass with proteins, lipids, saccharides, inorganics, lignin and cellulose as main components (Li and Jiang, 2017).

[3] Any small organism, such as a virus or a bacterium

[4] The act of burning something completely; reducing it to ashes

[5] A practice to improve soil quality

Sarmah, 2019), thus MSS is a waste biomass and does not need to be grown specifically to produce biochar. In addition to that, the costs for the disposal of MSS, which are probably significant if a large part of the MSS is transported to the mainland as in the case of the Swedish island of Gotland, can be saved. This could in fact make BMSS economically viable.

1.1.2. Biochar Production with Pyrolysis

There are several methods used to produce biochar, and a common one is pyrolysis, which describes the thermochemical conversion of biomass in the absence of oxygen (Kwon, Lee and Sarmah, 2019). One differentiates between fast and slow pyrolysis. Slow pyrolysis has a slow heating-rate, generally leading to higher yield and a more stable material, whereas fast pyrolysis operates with a fast heating-rate (Kwon, Lee and Sarmah, 2019), leading to more bio-oil than biochar production (Ok, et al., 2016). The production of BMSS not only demands for the pyrolysis itself but also for a pre-drying process beforehand.

1.1.3. Previous Literature

The pyrolysis technology to produce biochar has been researched quite extensively. Therefore, several studies can be found that consider MSS as a feedstock: A study by Trabelsi, et al. (2021) explored the optimal pyrolysis temperature and sewage sludge moisture content and identified 550°C as being optimal with a 15% moisture content of the sewage sludge feedstock. This has led to a biochar yield of 52 wt% (Trabelsi, et al., 2021). Agrafioti, et al. (2013) also studied the factors which could affect the biochar yield by pyrolyzing sewage sludge and concluded that the pyrolysis temperature is the main influencing factor. The highest yield was achieved at 300°C and it was shown that the surface area of biochar increased with increasing pyrolysis temperature, but a maximum was reached with chemical impregnation (Agrafioti, et al., 2013). Another finding by

Agrafioti, et al. (2013) reveals that heavy metal release from biochar is suppressed through pyrolysis, enabling the use of BMSS as soil amendments in the USA. Moreira, Noya and Feijoo (2017) performed a literature review from a lifecycle perspective to compare a variety of feedstocks for biochar production. It was concluded that all of them perform well for climate change mitigation, but lignocellulosic based materials show the highest environmental benefits (Moreira, Noya and Feijoo, 2017). Other studies focus on the applications of biochar from sewage sludge after production and tested the effects of biochar in agricultural land. Zhang, et al., (2021) tested sewage sludge and its biochar in soil, growing corn and radish in a one-year field trial. They used different amounts of sewage sludge and biochar and concluded that the highest yield of corn and radish was produced when applying 15 t BMSS per hectare. Even though the heavy metal content in BMSS was found to be higher compared to the input biomass due to the fact that the pyrolysis process increases the concentration of the existing heavy metal content of the input biomass in the conversion process, no human health risks were found for the consumption of the grown plants (Zhang et al., 2021). It can be added that the World Energy Outlook, written by the International Energy Agency (2019) mentions biochar production as one of four options that are able to achieve large-scale negative emissions. The only concerns relate to the uncertainties of negative consequences on land use, biodiversity and food security, as the mentioned technologies by the IEA have not yet been tested on a large scale (International Energy Agency, 2019). This points out the currently existing knowledge gap regarding biochar: the production and implementation on a larger scale and the production and application of biochar with waste products such as MSS.

1.1.4. MSS Treatment on Gotland

Gotland has waste-water treatment plants in three towns: Visby, Klintehamn and Slite. The sewage from areas and houses not connected to the pipes that lead to those treatment plants is picked up separately and transported to the plants. In Visby alone, 8000 m^3

wastewater is collected per day of which organic biomass (sewage sludge) is a significant amount (Region Gotland, 2019a). In Visby's wastewater treatment plant, MSS is separated from the wastewater and in a second step, the sludge undergoes a stabilization process to eliminate the smell, by converting the easily decomposable solid organic substances to a gaseous form (Region Gotland, 2019b). During that process, the amount of MSS is reduced by around 40% and the gas is used for fueling vehicles (Region Gotland, 2019b). Together with a big portion of the sludge from Klintehamn, it is then pumped into digestion chambers and warmed up to 55°C, which hygienizes the material. Excess heat from that process sums up to around 5 GWh per year and is used for heating up the facility buildings, and the sewage sludge in the digestion chambers as well as for the district heating system (Region Gotland, 2019a). After that it is pumped to another facility where it is centrifuged for further de-watering. It is then transported to a storage facility in Roma by a contractor of Region Gotland. *Table 1* presents the amounts of MSS as well as its dry matter and water content for the year 2018 from all three waste-water treatment facilities. It is not entirely traceable for what the MSS from Slite was used for, but it can be assumed that it was picked up by the contractor and transported to the mainland, together with 2,826 t from the other two facilities (Region Gotland, 2018a; Region Gotland, 2018b). The remaining 551 t were used on Gotland for fields and soil improvement (Region Gotland, 2018a). Only the MSS that runs through the facility in Visby can be used as fertilizer on agricultural land as it is the only facility that produces MSS that qualifies for a so called Revaq certificate. MSS without that certificate is not allowed to be used as soil fertilizer in Sweden (Finnson, 2022). The costs for the transportation of MSS to the mainland are 800 SEK per t for certified MSS and 1,100 SEK per t for non-certified MSS (Region Gotland, 2022). As the MSS from Slite and Klintehamn is not certified the annual costs result in about 911,900 SEK. Adding to that the transportation of the certified MSS from Visby which is 1,597,600 SEK annually.

Table 1: Total amounts of treated MSS from the three waste-water treatment plants on Gotland in 2018, including dry matter contents and water content (Region Gotland, 2018a; Region Gotland 2018b; Region Gotland 2018c).

	Amount		Ts-content	Water content
Visby	2,548	t	32.3%	67.7%
Slite	303	t	31%	69%
Klintehamn	526	t	23%	77%
Total	3,377	t	31%	69%

Table 2: Heavy metal contents in MSS from Visby's waste-water treatment plant in 2019 (Region Gotland, 2022).

Heavy Metal[6]	**Pb**	**Hg**	**Cd**	**Cu**	**Cr**	**Ni**	**Zn**	**Ag**	**Sn**	**Bi**
Unit	mg/kg Ts	mg/kg Ts	mg/kg Ts	mg/kg Ts	mg/kg Ts	mg/kg Ts	mg/kg Ts	mg/kg Ts	mg/kg Ts	mg/kg Ts
Average value	12.52	0.29	0.71	952.5	17.5	8.12	611.7	1.36	13	3.56
Minimum value	9.6	0.18	0.56	770	14	5.8	520	0.98	11	2.9
Maximum value	17	0.52	0.87	1300	21	12	740	2	17	4.3

As mentioned above in previous literature, special attention needs to be paid to the heavy metal content in the MSS and afterwards in the biochar. This is due to the potential leaking of the heavy metals in soil and absorption in plants. *Table 2* presents the heavy metal contents for the treated MSS from Visby in 2019.

1.2. Aim and Scope

It can be assumed that Gotland is a potential area for implementing the production of biochar via pyrolysis of MSS as most of the MSS is currently transported to the mainland where it ends up on landfills and coverage of dumps (Region Gotland, n.d.). This procedure is responsible for a significant amount of greenhouse gases due to transportation of the MSS and its decomposition on landfills as well as a significant amount of costs, as

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[6] Lead (Pb); Mercury (Hg); Cadmium (Cd); Copper (Cr); Nickel (Ni); Zinc (Zn); Silver (Ag); Tin (Sn); Bismuth (Bi)

mentioned above. The emissions could be avoided by producing biochar directly on Gotland and even act as a carbon sink and maybe used as amendment in agricultural soil or other fields of application, like as a cement substitute in the construction sector. It can be added that the direct application of MSS in agricultural soil is limited in Sweden as it is not allowed to apply it to soil used for the production of berries, potatoes, root vegetables, vegetables and fruits (except tree-growing fruits), as well as on arable or grazable land where harvest is expected within 10 months after distribution (Jordbruksverket, 2021). However, the application of BMSS to agricultural land for food production might be possible depending on the content of contaminants and heavy metals in the produced biochar from Gotlandic MSS. Region Gotland points out that knowledge about a more circular use of the MSS on the island is currently missing (Region Gotland, n.d.). Adding to that, the Swedish government decided already in 2018 to investigate the potential for the recycling of P from MSS as well as prohibition of applying MSS to agricultural land (Hållbar slamhantering, 2020). A report was published in 2020 that suggests, amongst others, the replacement of direct MSS application with BMSS (Hållbar slamhantering, 2020). However, it is also mentioned that rules and regulations have to be found for the application of biochar (Hållbar slamhantering, 2020).

This leads to the aim of this study, which is to examine the potential of producing biochar from MSS in a pyrolysis reactor on Gotland, including an assessment of the energy input and output of a potential biochar production system, possible fields of application on Gotland as well as the carbon sequestration potential. This is done via a review of documents, the gathering of grey literature and through contacts and experts in the field. The study addresses the following questions:

1. What is the energy and mass balance of biochar production from sewage sludge via pyrolysis on Gotland?
2. What are possible applications of biochar on Gotland considering the expected heavy metal contents of the produced biochar?
3. What is the carbon sequestration potential of the produced biochar focusing on the direct carbon storage in the biochar?

This study is delimited to the above presented questions. *Figure 1* represents the system boundary for the first research question and with that the processes that were included in the calculation for the energy and mass balance. The inputs to the system are electricity and MSS and the output considered is the amount of biochar produced and not the exhaust gas, which could potentially be emissions from processing the MSS. Moreover, only MSS that was processed in the waste-water treatment plants on Gotland in 2018 was included in this study, since this information was publicly available. The second research question is only considering the expected heavy metal contents of the MSS from the waste-water treatment plant in Visby, due to lack of information from the other waste-water treatment sites. The third question only takes into consideration the carbon that would be stored in the BMSS as well as the theoretical amount of CO2 that is not emitted into the atmosphere. The results will not be compared to other and current uses of MSS, like landfill or soil amendment. There are other aspects that are excluded from this study like economic factors such as the cost calculation of the biochar production system.

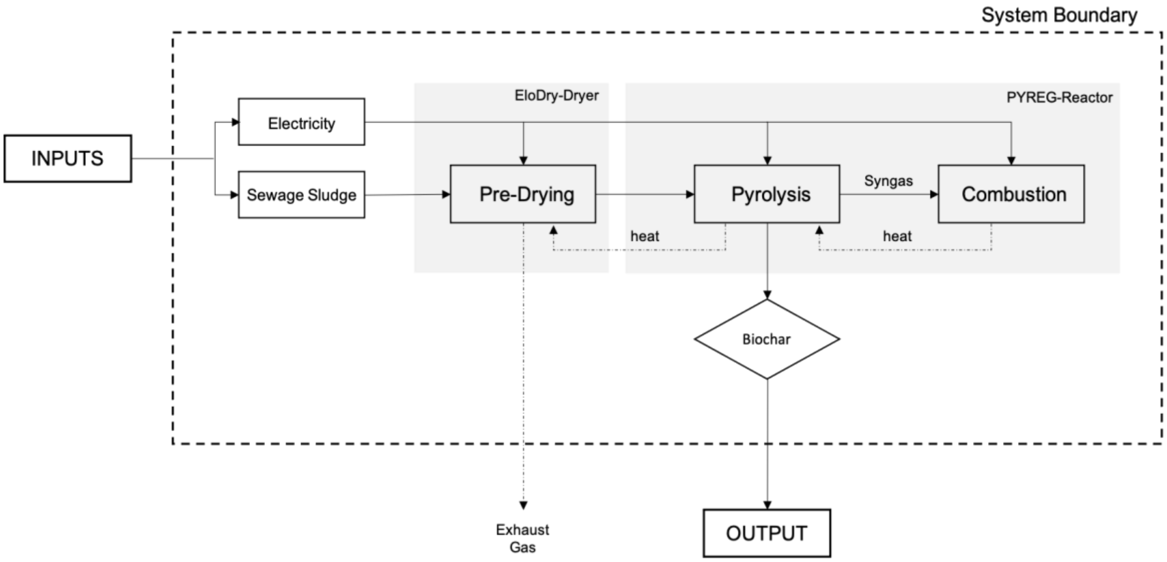


Figure 1: System Boundary of a potential pyrolysis plant on Gotland, producing biochar from sewage sludge.

2. Theory & Data

2.1. Energy and Mass Balance Calculations

In order to answer the first research question and calculate the energy and mass balance of a potential BMSS production system, several steps were taken. *Figure 2* displays those steps, and it is described thoroughly in section *3. Methods and Data* how these were approached. The first step, Define System Boundaries, was already presented in section *1.2. Aim and Scope* and research was done on existing technologies. The technologies for the pre-drying process and the pyrolysis process that were found suitable as well as the equations used for the calculation of the energy and mass balance are presented below.

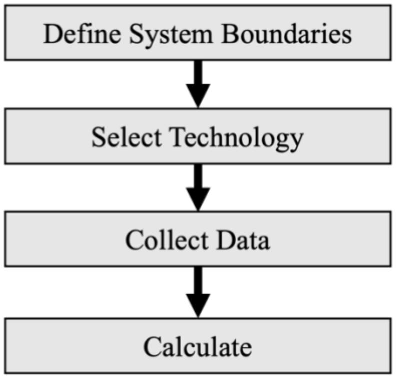


Figure 2: The four steps of calculating the energy and mass balance.

2.1.1. The Technologies

The BMSS production system requires a pre-drying process as well as a pyrolysis process. The following two technologies comply with each other and are therefore suitable for the production of BMSS.

EloDry is a fully automatic low-temperature belt dryer produced by the company ELIQUO, specifically constructed for drying MSS (ELIQUO, 2022). It is a highly energy efficient technology and compatible with a pyrolysis reactor, as the excess heat from the pyrolysis process can be used to dry the MSS (ELIQUO, 2022). The EloDry belt dryer is available in different sizes, due to the identical intermediate segments which can be added depending on the drying capacity needed (ELIQUO, n.d.). The input material can already be dewatered or pre dried and the process heat should optimally lie around 70°C (ELIQUO, n.d.). The technology prevents the release of emissions due to the operation in a slight vacuum (ELIQUO, n.d.).

Table 3: System calculations for the EloDry unit (ELIQUO, 2022).

ELODRY NT16	**AMOUNT**	**UNIT**
Water evaporation capacity per h	0,44	t
Heat demand per t evaporated water	750	kWhth
Power demand per t evaporated water	50	kWh_{el}

PYREG is a German company that focuses on the development of carbonization technologies (PYREG, 2021a). The company builds decentralized pyrolysis reactors that can convert the input biomass completely into biochar (PYREG, 2021a). The process temperature is around 600-700°C and the input material should have at least 80% dry matter content (PYREG, 2022). Depending on the size of the processor, the technology can handle between 1,070t and 2,870t of MSS and produces with that between 540t to 1,440t of biochar annually (PYREG, 2021b). Moreover, it is an autothermal technology, meaning that the energy generated from the combustion of the syngas is sufficient to run the pyrolysis process (PYREG, n.d.). The pyrolysis excess energy of 1,125GWh to 5,250GWh, depending on the size of the unit, can be used to dry the input biomass or for a district heating system (PYREG, 2021b). The produced biochar from MSS does not contain any residues of pharmaceuticals or other contaminants (PYREG, 2022) but the phosphorus of the input biomass is captured in the biochar and will be partly available to plants, once put in soil (PYREG, 2021b). Overall, the PYREG technology qualifies for the European Biochar Certificate (EBC) (PYREG, n.d.).

Table 4: Technology characteristics for the smallest PYREG unit, based on MSS with 90% dry-matter content as input (PYREG, 2021b).

PYREG P500	**Amount**	**Unit**
Combustible rating	500	kW
Annual throughput	1,070	t
Annual production	540	t
Excess heat power	150	kW_{th}
Annual excess heat energy	1,125,000	kWh_{th}
Annual operation hours	7,500	h
Power consumption	16	kW_{el}

2.1.2. Equations

The energy and mass balance calculations are based on the technologies presented in *Section 2.1 Energy and Mass Balance Calculation*. as well as the total annual MSS on Gotland in 2018 as it was shown in *Table 1*. The equations that were used for the calculations can be found in *Table 5 below*. *Equation 1* calculates the dry substance M_t of MSS by multiplying the total amount of MSS S_t times the TS-content T_s whereas *Equation 2* calculates the water mass W_t in the same way by multiplying the value for the water content W instead. *Equation 3* calculates the amount of MSS mass with 90% dry substance M_{dry90} and *Equation 4* the water mass in MSS with 90% dry substance W_{dry90}. *Equation 5* calculates then the amount of water that needs to be evaporated W_{evap} in order for the MSS to have 90% dry substance by subtracting the total water mass in the MSS W_t calculated by *Equation 2* with the water mass in MSS with 90% dry substance W_{dry90}. *Equation 6* calculates the mass ratio R of the pyrolysis process by dividing the annual BMSS production A_p by the annual MSS throughput A_t and *Equation 7* calculates the MSS surplus S_s as the pyrolysis reactor is not able to handle more than 1,070 t of MSS annually, by subtracting the MSS mass with 90% dry substance M_{dry90}, which is the input of the pyrolysis process by the annual throughput A_t. In *Equation 8*, the annual throughput A_t is divided by the annual operation hours A_h to calculate the MSS throughput per hour S_h. *Equation 9* calculates the annually excess heat energy A_{th} produced by the pyrolysis process by multiplying the annual operation hours A_h times the excess heat power H_p

Equations	Definitions	Unit
$M_t = S_t T_s$ (1)	$A_{e-elodry}$ = Annual electricity consumption	kWh$_{el}$
	$A_{e-pyreg}$ = Annual electricity consumption	kWh$_{el}$
$W_t = S_t W$ (2)	A_{el} = Annual electricity demand	kWh$_{el}$
	A_h = Annual operation hours	h
$M_{dry90} = \frac{M_t}{1-0.9}$ (3)	A_{he} = Annual net heat energy demand	kWh$_{th}$
	A_p = Annual BMSS production	t
	A_t = Annual MSS troughput	t
$W_{dry90} = \frac{M_t}{1-0.1}$ (4)	A_{th} = Annual excess heat energy	kWh$_{th}$
$W_{evap,} = W_t - W_{dry90}$ (5)	H_e = Annual heat energy demand	kWh$_{th}$
	H_p = Excess heat power	kW$_{th}$
$R = \left(\frac{A_p}{A_t}\right)$ (6)	H_t = Heat demand per t evaporated water	kWh$_{th}$
	M_{dry90} = MSS with 90% dry substance	t
$S_s = M_{dry90} - A_t$ (7)	M_t = Dry substance	t
	P_t = Power demand per t evaporated water	kWh$_{el}$
$S_h = \frac{A_t}{A_h}$ (8)	S_h = Hourly MSS throughput	t
	S_S = Surplus MSS	t
$A_{th} = A_h H_p$ (9)	S_t = Total MSS	t
	T_s = Ts content	%
	W_c = Water evaporation capacity per h	t
$A_{e-pyreg} = A_h P$ (10)	W_{dry90} = Water mass in MSS with 90% dry substance	t
	$W_{evap.}$ = Water to be evaoprated	t
$W_h = \frac{W_{evap.}}{A_h}$ (11)	W_h = Water evaporation per h	t
$H_e = W_{evap.} H_t$ (12)	W_t = Water mass	t
	C = Combustible rating	kW
$A_{e-elodry} = W_{evap.} P_t$ (13)	P = Power consumption	kW$_{el}$
	R = Mass ratio	-
	W = Water content	%
$A_{he} = A_{th} - H_e$ (14)	$A_{e-elodry}$ = Annual electricity consumption EloDry	kWh$_{el}$
$A_{el} = A_{e-pyreg} + A_{e-elodry}$ (15)	$A_{e-pyreg}$ = Annual electricity consumption PYREG	kWh$_{el}$

Table 5: All Equations used for the energy and mass balance calculations.

whereas *Equation 10* calculates the annual electricity consumption of the PYREG reactor $A_{e-pyreg}$ by multiplying the annual operation hours A_h by the power consumption P. *Equation 11* calculates the amount of water that needs to be evaporated per hour W_h by dividing the total amount of water that needs to be evaporated $W_{evap.}$ by the annual operation hours A_h. *Equation 12* multiplies the water that needs to be evaporated $W_{evap.}$ by the heat demand per t evaporated water H_t to calculate the annual heat energy demand H_e of the drying process. *Equation 13* multiplies the water that needs to be evaporated $W_{evap.}$ by the power demand per t evaporated water P_t to calculate the annual electricity consumption $A_{e-elodry}$ of the drying process. *Equation 14* calculates the annual net heat energy demand A_{he} resulting from both processes by subtracting the annual excess heat energy A_t from the pyrolysis process by the annual heat energy demand from the drying process H_e. And finally, *Equation 15* calculates the annual electricity demand for the whole system by adding the annual electricity consumption from the EloDry technology $A_{e-elodry}$ and the annual electricity consumption from the PYREG technology $A_{e-pyreg}$.

2.2. Heavy Metal Content Calculations

As for the second research question, the expected quality of the produced BMSS was approached by evaluating the heavy metal contents. The answering of that question was addressed by following the steps presented in *Figure 3*.

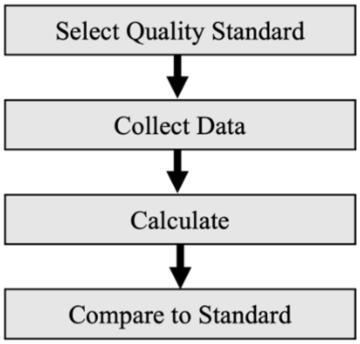


Figure 3: Steps taken for the quality evaluation of the BMSS.

To simulate a worst-case scenario, it was assumed that none of the heavy metals evaporate during the pyrolysis process. This means that the weight of heavy metals would stay the same and only has to be divided by the mass ratio that was calculated with *Equation 6*. Therefore, the equation used for the calculation of the expected heavy metal contents in the BMSS, based on the numbers from *Table 2*, can be seen in *Table 6*.

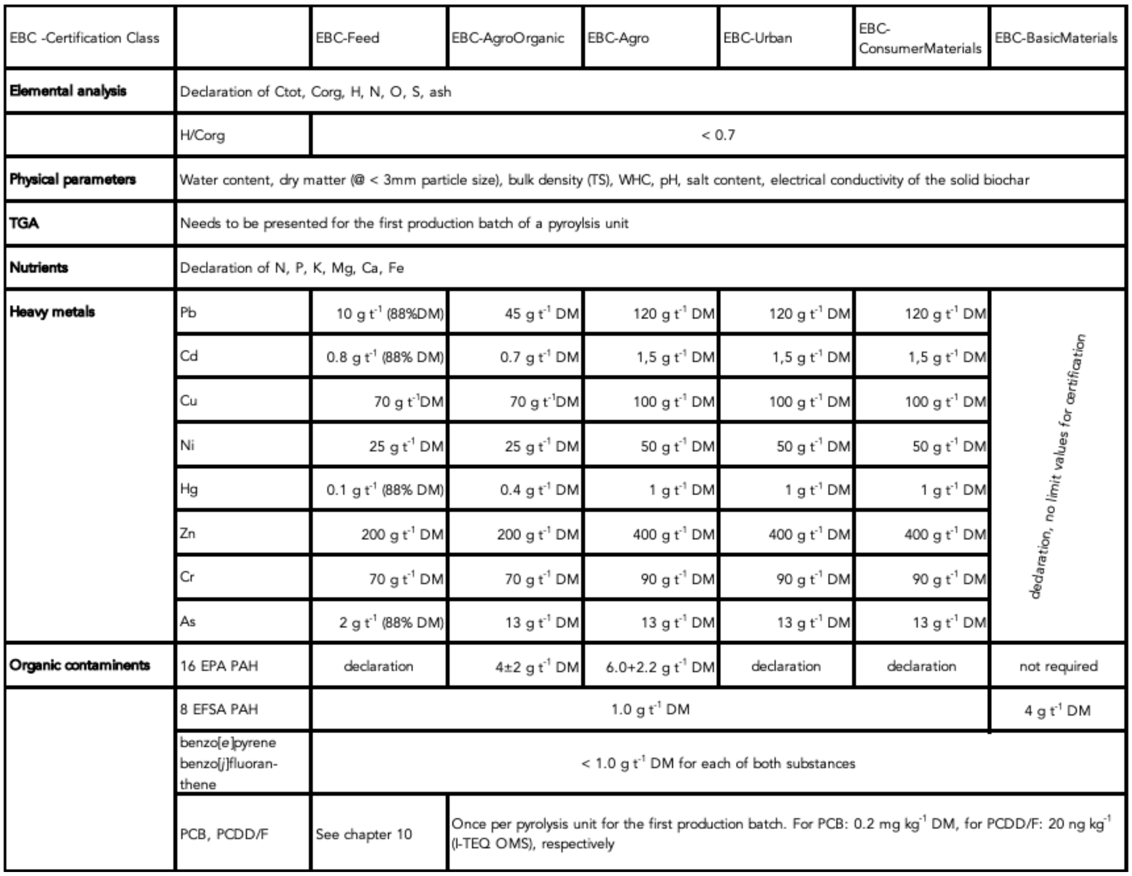
Equations	Definitions	Unit
$H_{bmss} = \frac{H_{mss}}{R}$ (16)	$H_{mss} = Heavy\ metal\ content\ in\ MSS$	mg/kg
	$H_{bmss} = Heavy\ metal\ content\ in\ BMSS$	g/t
	$R = Mass\ ratio$	-

Table 6: Equation for heavy metal content calculation in BMSS.

2.2.1. The European Biochar Certificate

The EBC was chosen as a quality standard to evaluate what applications might be possible from BMSS. The EBC provides guidelines and acts as a control and assessment system for the sustainable production and analysis of biochar (EBC, 2022). This guarantees the abidance of quality standards for the costumer as well as the producer (EBC, 2022). The EBC has a variety of certification classes which refer to the application of biochar in which different parameters are controlled and different limit values apply (*Table 3*). Moreover, the EBC is updated on a regular basis to be in line with recent research and technology, but also to adapt to European legislation (EBC, 2022). Sweden has approved the use of EBC certified biochar but has added the Sweden Annex of the EBC which sets limits beyond the EU regulation (EBC, 2022). It is seen as an addendum to the EBC and overrules it in certain limit values for the EBC-Agro and EBC-AgroBio certification classes for the Swedish market (EBC, 2022). For the EBC-Agro certificate, Pb cannot exceed 100 mg per kg and Cd 1 mg per kg of biochar. In order to get an EBC-AgroBio certificate in Sweden, an analysis of the Ag content has to be carried out. So far, MSS is not included in the EBC feedstock list, like other non-plant biomasses, but they are seen as valuable raw materials that will be reviewed by mid-2022 and a document about product safety and conditions will be published (EBC, 2022). Besides the guidelines for feedstock, the EBC also ensures that no fossil fuels are used for the production of biochar and demands that at least 70% of the excess heat from the pyrolysis process has to be used for sustainable processes like district heating or the drying process of the biomass feedstock (EBC, 2022).

Table 7: EBC certificate classifications and limit values for different applications of biochar in Europe (EBC, 2022).



EBC -Certification Class		EBC-Feed	EBC-AgroOrganic	EBC-Agro	EBC-Urban	EBC-ConsumerMaterials	EBC-BasicMaterials
Elemental analysis	Declaration of Ctot, Corg, H, N, O, S, ash						
	H/Corg	< 0.7					
Physical parameters	Water content, dry matter (@ < 3mm particle size), bulk density (TS), WHC, pH, salt content, electrical conductivity of the solid biochar						
TGA	Needs to be presented for the first production batch of a pyroylsis unit						
Nutrients	Declaration of N, P, K, Mg, Ca, Fe						
Heavy metals	Pb	10 g t^{-1} (88%DM)	45 g t^{-1} DM	120 g t^{-1} DM	120 g t^{-1} DM	120 g t^{-1} DM	declaration, no limit values for certification
	Cd	0.8 g t^{-1} (88% DM)	0.7 g t^{-1} DM	1,5 g t^{-1} DM	1,5 g t^{-1} DM	1,5 g t^{-1} DM	
	Cu	70 g t^{-1}DM	70 g t^{-1}DM	100 g t^{-1} DM	100 g t^{-1} DM	100 g t^{-1} DM	
	Ni	25 g t^{-1} DM	25 g t^{-1} DM	50 g t^{-1} DM	50 g t^{-1} DM	50 g t^{-1} DM	
	Hg	0.1 g t^{-1} (88% DM)	0.4 g t^{-1} DM	1 g t^{-1} DM	1 g t^{-1} DM	1 g t^{-1} DM	
	Zn	200 g t^{-1} DM	200 g t^{-1} DM	400 g t^{-1} DM	400 g t^{-1} DM	400 g t^{-1} DM	
	Cr	70 g t^{-1} DM	70 g t^{-1} DM	90 g t^{-1} DM	90 g t^{-1} DM	90 g t^{-1} DM	
	As	2 g t^{-1} (88% DM)	13 g t^{-1} DM	13 g t^{-1} DM	13 g t^{-1} DM	13 g t^{-1} DM	
Organic contaminents	16 EPA PAH	declaration	4±2 g t^{-1} DM	6.0+2.2 g t^{-1} DM	declaration	declaration	not required
	8 EFSA PAH	1.0 g t^{-1} DM					4 g t^{-1} DM
	benzo[*e*]pyrene benzo[*j*]fluoranthene	< 1.0 g t^{-1} DM for each of both substances					
	PCB, PCDD/F	See chapter 10	Once per pyrolysis unit for the first production batch. For PCB: 0.2 mg kg^{-1} DM, for PCDD/F: 20 ng kg^{-1} (I-TEQ OMS), respectively				

2.3. Carbon Sequestration Potential Calculation

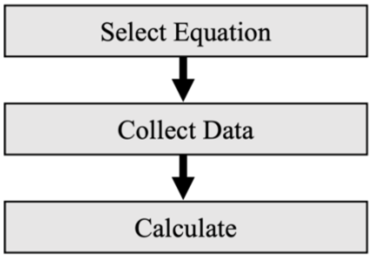


Figure 4: Steps taken to calculate the carbon sequestration potential of the produced BMSS.

In order to estimate the carbon sequestration potential, the three steps presented in *Figure 4* were followed. It was calculated based on a calculation done by Meyer, et al. (2012). That study investigated how biochar in soil changes the surface albedo as well as the impact on the carbon cycle. One part of their equation was used in order to calculate the amount of CO_2 sequestered by biochar, displayed by

Equation 19. For this calculation, two other equations are needed beforehand. Firstly, it has to be calculated how much carbon is contained in the amount of produced BMSS, which is presented by *Equation 17*. The annual production is part of the first research question so the value will be known later on and as for the amount of carbon in pyrolyzed MSS at 700°C, 18% were obtained from findings by Quicker and Weber (2016). With *Equation 18*, the atomic weight of CO_2 can be calculated. The results are then used in *Equation 19*, where the actual weight of the CO_2 that is spared by storing the carbon in biochar. This is done by multiplying the amount of carbon in the pyrolyzed MSS times the ratio of the molecular weight of CO_2 to the weight of carbon.

Table 8: Equations used for carbon sequestration potential calculation.

Equations	Definitions	Unit
$C = \frac{(A_p C_\%)}{100}$ (17) $M_{co2} = AW_c + (2AW_o)$ (18) $S_{co2} = C\frac{M_{co2}}{MW_c}$ (19)	$A_p = Annual\ production$	t
	$C_\% = Carbon\ content\ in\ pyrolysed\ MSS\ at\ 700°C$	%
	$AW_c = Atomic\ weight\ of\ carbon = 12$	amu[7]
	$AW_o = Atomic\ weight\ of\ oxygen = 16$	amu
	$M_{co2} = Molecular\ weight\ of\ CO_2$	amu
	$C = Carbon\ in\ pyrolysed\ MSS$	t
	$S_{co2} = Annual\ amount\ of\ CO_2\ saved$	t

3. Methods

3.1. Philosophical Worldview and Research Approach

This study is written with the post-positivistic worldview described by Creswell and Creswell (2018) as a philosophical base. This worldview is crucial for this study as it mostly focuses on the gathering of data to understand the potential for the production and application of biochar from MSS with a pre-drying process and pyrolysis reactor on Gotland as well as to calculate the mass and energy input and output of such a system. It

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[7] Atomic mass unit

also indicates a quantitative methodology as the research approach, as such an approach is used for testing objective theories with its findings being possible to generalize or replicate (Creswell and Creswell, 2018).

3.3. Case study

The case presented in his study is the island of Gotland. It can be seen as a system that already has its boundaries due to its geographical location in the Baltic Sea. Gotland has been analysed by focusing on the aspects relevant to the research questions as described by Yin, R.K. (2018). That includes the availability of MSS, its current use and the possibility for biochar production. The data analysed was following the data collection steps explained in the following section.

3.4. Document Review and Data Collection

The collection of data is an important phase for all research questions and especially for the calculation of energy and mass balance of the pyrolysis and the pre-drying technology. In this study, the document review and collection of data go hand-in-hand. For the second and third step of the energy and mass balance calculations (see *Figure 2*), document reviews were conducted after searching for existing and suitable pre-drying and pyrolysis technologies. The information and data for both technologies were abstracted from both, grey literature as well as documents from the PYREG and EloDry company which are publicly available. The company PYREG was consulted in order to double check information found on their website. More data was found in documents from Region Gotland which provided the necessary information regarding MSS availability on Gotland.

For the first and second step of the quality evaluation of the BMSS (see *Figure 3*), the EBC standard document was reviewed. It is a publicly available document and was therefore found suitable for this study. Information regarding heavy metal contents in the

MSS on Gotland was not found, so local experts from Region Gotland were asked who filled in the information gaps.

As for the third question, studies were reviewed in order to find a method and equation for the calculation of the carbon sequestration potential.

3.5. Ethical Considerations

Ethical aspects can be found within the gathering and handling of data in this study. First, it must be considered where numeric data is taken from. Data extracted from grey literature was often double-checked through experts. Also, the author of this study tried to be transparent with the data and calculations that were delt with. That means to state where data comes from, to explain equations, to avoid plagiarism and to include negative results, if found, to avoid subjectivism. Experts and other contacts were informed about the purpose of this study and are not mentioned by name.

4. Results

The following three sections present the results of this study. They are divided according to the order of the research questions, starting with the presentation of the energy and mass balance of the biochar production system, which is shown in *Figure 1.* After that, *Section 4.2.* is about the expected biochar quality and resulting from that the potential applications for BMSS, considering the expected heavy metal contents. Lastly, the results for the carbon sequestration potential are presented in *Section 4.3.*

4.1. Energy and mass balance

The following table (*Table 9*) shows the total amounts of dry matter and water content of the available MSS on Gotland. The water content of the MSS needs to be reduced to 10% water content before entering the PYREG pyrolysis reactor. Conclusively, the amount of water that needs to be evaporated with the EloDry technology drying process is 2,224 t.

Table 9: Available MSS on Gotland in 2018, including the calculated amount of MSS with 90% dry-matter content and the amount of water that needs to be evaporated in the pre-drying process.

MSS RG 2018	Visby		Slite		Klintehamn		Total	
Dry substance	823	t	94	t	121	t	1,038	t
Water mass	1,725	t	209	t	405	t	2,339	t
MSS with 90% dry substance							1,153	t
Water to be evaporated							2,224	t

This leads to the next table (*Table 10*) which shows the energy needs of the pre-drying process with the EloDry technology. The amount of water to be evaporated determined the size of the technology, as the hourly water evaporation must be 0.30 t and the smallest unit of the EloDry cannot handle that.

Table 10: The energy needs of the pre-drying process, based on the amount of water that needs to evaporate.

Pre-Drying	Amount	Unit
Water evaporation per h	0.30	t
Annual heat energy demand	1,667,822	kWh_{th}
Annual electricity consumption	111,188	kWh_{el}

Therefore, the next bigger unit was chosen with a capacity of 0.44 t per h (ELIQUO, 2022). The water evaporation capacity of 0.30 t per h was calculated by the total amount of water to be evaporated (*Table 9*) divided by the annual operation hours (*Table 11*). The annual heat energy demand of 1,667,822 kWh and the annual power consumption of 111,188 kWh to carry out the drying are also presented in *Table 9*.

The next table (*Table 11*) presents all results concerning the pyrolysis process with the PYREG technology. As also presented in *Table 2*, the maximal annual throughput of MSS is 1,070 t and the annual biochar production is 540 t which leads to an input-output ratio of around 50% and a MSS surplus of 83 t per year. With annual operation hours of 7,500 h, this leads to an hourly input of 0.14 t of MSS with 90% dry matter content. The amount of annual excess heat energy sums up to 1,125,000 kWh and the annual electricity consumption accounts for 120,000 kWh.

*Table 11: Energy needs and possible amount of BMSS production with the PYREG technology (*90% dry-matter content).*

Pyrolysis	**Amount**	**Unit**
Mass ratio	0.5	-
Annual throughput *	1,070	t
Annual production	540	t
Surplus MSS *	83	t
Hourly MSS throughput *	0.14	t
Annual operation hours	7,500	h
Annual excess heat energy	1,125,000	kWh_{th}
Annual electricity consumption	120,000	kWh

Looking at the total annual energy and mass balance of the system, which is presented in *Table 12*, the total MSS input accounts for 3,377 t and the biochar production for 540 t. The total annual heat demand for the pre-drying process is 1,667,822 kWh. After subtracting the excess heat from the pyrolysis process, the remaining thermal energy demand only accounts to 542,822 kWh annually. The total electricity demand sums up to 231,188 kWh.

Table 12: Energy and mass balance outcomes.

Energy And Mass Balance	**Amount**	**Unit**
Annual MSS throughput	3,377	t
Annual BMSS production	540	t
Annual net heat energy demand	542,822	kWh_{th}
Annual electricity demand	231,188	kWh_{el}

4.2. Expected BMSS Quality

The quality of the produced BMSS with the above-mentioned system is determining the applications on Gotland afterwards. Therefore, BMSS must be analyzed for heavy metal contents, which can then be compared to the limit values of the EBC to determine possible applications.

4.2.1. Heavy Metal Content

It was assumed that heavy metals do not evaporate during the pyrolysis process. This means that the actual weight of heavy metals stays the same, but as the ratio of input and output of MSS mass in the pyrolysis was calculated to be 50% (*Table 11*), the heavy metal content doubles per t of biochar. *Table 13* presents the expected heavy metal content in grams per ton biochar of the MSS from the wastewater treatment plant in Visby in 2019.

Table 13: Expected heavy metal contents in the produced BMSS, based on the values from Table 2.

Heavy Metal	**Pb**	**Hg**	**Cd**	**Cu**	**Cr**	**Ni**	**Zn**	**Ag**	**Sn**	**Bi**
Unit	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts
Average value	25.03	0.57	1.43	1,905	35.00	16.23	1,223	2.71	26.00	7.12
Minimum value	19.20	0.36	1.12	1,540	28.00	11.60	1,040	1.96	22.00	5.80
Maximum value	34.00	1.04	1.74	2,600	42.00	24.00	1,480	4.00	34.00	8.60

4.2.2. Comparison with EBC

Comparing the expected values for heavy metal contents in BMSS (*Table 13*) to the limit values of the different EBC certification classes (*Table 7*), it can be determined what applications are possible for BMSS. It has to be noted, that the value for As is unknown and can therefore not be taken into account for the comparison. However, with the calculated heavy metal contents, BMSS is only suitable for the EBC-BasicMaterials certification class, as this category has no limit values for heavy metals. For all other certification classes, some of the expected heavy metal contents are too high. Comparisons for each certification class individually can be found in *Appendix A*. For EBC-Feed, the only heavy metals that would get a pass are Cr and Ni. For EBC-Agro, also Pb would pass as well as the smallest value for Hg. For the EBC-Agro, -Urban and -ConsumerMaterials, most of the heavy metals would pass expect Cu and Zn. It can be pointed out that the average value of Cu is almost 20 times higher than allowed by the EBC standard and those of Zn three times higher. This, as mentioned above, means that the produced BMSS is only suitable for the EBC-BasicMaterials certificate.

4.3. Carbon Sequestration Potential

The results of the carbon sequestration potential are presented in *Table 14*. The amount of carbon in the pyrolyzed BMSS was found to be 97,2 t, as 540 t of BMSS are produced with an assumed 18% carbon content. The molecular weight of CO_2 results in 44 and was calculated by adding the amount of weight of one carbon atom to the amount of weight of two oxygen atoms as this is the constellation of CO_2. This leads to the result for the annual amount of CO_2 that is saved or, in other words, not released into the atmosphere. By multiplying the total amount of carbon in the produced BMSS with the ratio of CO_2 to carbon it was calculated that around 356 t of CO_2 per year would not be released by the production of BMSS on Gotland.

Table 14: Carbon sequestration and CO_2 savings potential.

Carbon Sequestration	**Amount**	**Unit**
Carbon in pyrolyzed BMSS	97,2	t
Molecular weight of CO_2	44	amu
Annual amount of CO_2 saved	356,4	t

5. Discussion and Analysis

The results presented above give a valuable understanding on how a BMSS production system on Gotland could look like as well as what the produced BMSS could be used for and how much carbon could be sequestered in the biochar. It has to be noted that the results for the energy and mass balance are based on data from 2018, which means that results for other years can look differently. Especially with an increasing population, MSS availability is likely to increase as well, and the presented system could be easily expanded, with the addition of more units. Moreover, the water content for the input MSS into the PYREG technology can be as high up as 20 %, which would also lead to a different result than presented in this study and would probably slightly influence the heat and electricity demand for the production system. Another factor that influences the results is the amount of MSS available on Gotland.

The results for the energy and mass balance in *Table 12* unveil that the BMSS production system could not act autothermal but needs around 543 MWh per year on top of the annually produced thermal energy from the pyrolysis technology. Heat is usually costly if powered by electricity, so a different heat source to compensate for the deficiency would be preferable. An option here would be the excess heat produced from the hygienization process of MSS in the digestion chambers in Visby as explained in *Section 1.1.5*. The current annual heat production of that process is around 5 GWh, of which just around 10% would be needed for the net heat energy demand of the pre-drying process. Moreover, as most of the MSS comes from the wastewater treatment plant in Visby, it would be most advantageous to locate a BMSS production system close or even right next to the wastewater treatment plant, where the excess heat is produced and the MSS treated. The only issue there would be the transportation of the MSS from other treatment plants as well as the MSS from the centrifugation process, which takes place at a different location. Another result that can be pointed out is the annual electricity consumption, which sums up to 231 MWh. It would be preferable if the electricity needed would come from renewable sources to have an overall clean energy process. On Gotland there is a lot of wind power capacity and development for its extension which could be a convenient source. But also, the installation of solar panels on the roofs of the wastewater treatment plant in Visby could be a suitable option to cover some of the electricity needs as well as make profitable use of the non-used space. It can also be pointed out that the mass ratio of 50% does almost coincide with the mass ratio found by Trabelsi, et al. (2021), even though there has been a pyrolysis temperature difference of 50-150°C.

Regarding the heavy metal contents of the MSS presented in this study, they are an example of the year 2019 for only MSS from Visby and might look different in other years and for the MSS of the other treatment plants. It is however very unlikely, that the contents for Cu and Zn decrease to such an amount that would make the produced BMSS suitable for any other certificates than the EBC-BasicMaterials, as they are several times too high. Moreover, MSS as a feedstock for biochar production is not yet included in the EBC. The outcome of the review, mentioned by the EBC has to be awaited, before drawing any final conclusions about possible applications of the BMSS as well as the As content which is currently unknown. Nevertheless, the EBC-BasicMaterial certificate for the produced BMSS would make it possible to be used as replacement for cement. This would not only store the carbon for a long time but decrease emissions from the cement industry immensely. A study by De Carvalho Gomes, et al. (2022) tested the replacement of different amounts of cement with BMSS and raw MSS and refers to several studies that have looked into the possibility and potential for the use of BMSS in cement. One of those studies even claims that the concrete industry could sequester 0.5 Gt of CO_2 annually, if just 1% of BMSS substitute in cement would be used (De Carvalho Gomes, et al., 2022). This refers to approximately 20% of annual CO_2 emissions from the cement industry in 2020 (De Carvalho Gomes, et al., 2022; IEA, n.d.).

As mentioned in the introduction, the IEA has brought up concerns related to the uncertainties of negative consequences related to biochar production, such as land use and food security. It can however be pointed out that these concerns do not apply for BMSS as MSS is a waste product and no agricultural land would have to be used to produce biomass as feedstock, nor would it compete with food or energy crops. There is however a need for further research, dealing with the economic aspects of the BMSS production on Gotland in order to get a more specific picture of the full potential of such a system. Another aspect that can be looked into is the difference in limit values for EBC certificates in comparison with the limit values for direct MSS application in agricultural soil. As stated by the Swedish authority for agriculture, the MSS contents for Cu cannot exceed 600 g/t and for Zn 800 g/t of dry matter (Jordbruksverket, 2021). However, the biochar produced from MSS, where a leaching of heavy metals is proven to be reduced by pyrolysis if the conditions are right (Agrafioti, et al., 2013), is not allowed to exceed a maximum value of 100 g/t dry matter for Cu and 400 g/t for Zn according to the EBC standard. This means that the EBC sets much stricter heavy metal content limits for biochar application in agricultural soil compared to the limit values the Swedish state sets for MSS for the same application. Also, other values like the amount of Cr, Hg or Cd allowed in MSS for application in agricultural soil are higher than the limit values in the EBC (Jordbruksverket, 2021; EBC, 2022).

The results for the carbon sequestration potential indicate that in total 356,4 t of CO_2 are avoided and at the same time stored in the produced BMSS. This number does not include the avoided emissions from transporting the MSS to the mainland as it is still done today, meaning that even more emissions could be avoided by producing BMSS on Gotland. However, it cannot be said that this would be the amount of CO_2 saved compared to the current use, as this was not calculated in this study.

6. Conclusion

This study provides information about a potential production system on Gotland, which can turn MSS into valuable biochar, its energy and mass balance, possible applications as well as avoided GHG emissions. State-of-the-art technology that pre-dries and pyrolyzes the input material was chosen to calculate the annual energy and mass balance. The outcome shows that a significant amount of biochar could be produced to sequester carbon. Even though the pyrolysis system is an autothermal process with an annual excess heat production, it cannot cover the entire heat demand of the pre-drying process but around 2/3 of it. Thus, an additional heat source would be needed to cover the remaining 543,000 kWh. Moreover, a significant amount of electricity, around 230,000 kWh per year need to be covered by preferably a renewable electricity source.

The expected quality of the BMSS was investigated by calculating the heavy metal contents and comparing them to the limit values of the EBC. The results indicate that the BMSS only suitable for the EBC-BasicMaterial certification class, as the heavy metal contents are too high for any other certification class. This, however, might make BMSS possible to use as substitute in cement, which could significantly reduce the emissions of cement production.

Overall, the carbon sequestration potential of the produced BMSS was found to be around 356 t annually. This however does not include the avoided GHG emissions from the transportation of MSS to the mainland which would increase this potential even more. It can be added that not only emissions would be decreased but moreover a significant amount of transportation costs of MSS on Gotland.

Further research is needed in order to make a sufficient feasibility study about a biochar production system on Gotland. For this, more economic factors, research on possible locations as well as the impact of the exhaust gas from the BMSS production system must be investigated. Furthermore, the possibility of using the BMSS as a substitute in cement can be explored even further as it is such a new field of application. This could be especially interesting in cooperation with a local cement company, as transportation costs and emissions could be kept to a minimum and the company’s emissions could be decreased.

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APPENDIX A

EBC-Feed

Element	Pb	Hg	Cd	Cu	Cr	Ni	Zn	Ag	Sn	Bi
Unit	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts
Average value	25.03	0.57	1.43	1,905	35.00	16.23	1,223	2.71	26.00	7.12
Minimum value	19.20	0.36	1.12	1,540	28.00	11.60	1,040	1.96	22.00	5.80
Maximum value	34.00	1.04	1.74	2,600	42.00	24.00	1,480	4.00	34.00	8.60

EBC-AgroBio

Element	Pb	Hg	Cd	Cu	Cr	Ni	Zn	Ag	Sn	Bi
Unit	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts
Average value	25.03	0.57	1.43	1,905	35.00	16.23	1,223	2.71	26.00	7.12
Minimum value	19.20	0.36	1.12	1,540	28.00	11.60	1,040	1.96	22.00	5.80
Maximum value	34.00	1.04	1.74	2,600	42.00	24.00	1,480	4.00	34.00	8.60

EBC-Agro

Element	Pb	Hg	Cd	Cu	Cr	Ni	Zn	Ag	Sn	Bi
Unit	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts
Average value	25.03	0.57	1.43	1,905	35.00	16.23	1,223	2.71	26	7.12
Minimum value	19.20	0.36	1.12	1,540	28.00	11.60	1,040	1.96	22	5.8
Maximum value	34.00	1.04	1.74	2,600	42.00	24.00	1,480	4	34	8.6

EBC-Urban

Element	Pb	Hg	Cd	Cu	Cr	Ni	Zn	Ag	Sn	Bi
Unit	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts
Average value	25.03	0.57	1.43	1,905	35.00	16.23	1,223	2.71	26	7.12
Minimum value	19.20	0.36	1.12	1,540	28.00	11.60	1,040	1.96	22	5.8
Maximum value	34.00	1.04	1.74	2,600	42.00	24.00	1,480	4	34	8.6

EBC-ConsumerMaterials

Element	Pb	Hg	Cd	Cu	Cr	Ni	Zn	Ag	Sn	Bi
Unit	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts
Average value	25.03	0.57	1.43	1,905	35.00	16.23	1,223	2.71	26	7.12
Minimum value	19.20	0.36	1.12	1,540	28.00	11.60	1,040	1.96	22	5.8
Maximum value	34.00	1.04	1.74	2,600	42.00	24.00	1,480	4	34	8.6

EBC-BasicMaterials

Element	Pb	Hg	Cd	Cu	Cr	Ni	Zn	Ag	Sn	Bi
Unit	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts	g/t Ts
Average value	25.03	0.57	1.43	1,905	35.00	16.23	1,223	2.71	26	7.12
Minimum value	19.20	0.36	1.12	1,540	28.00	11.60	1,040	1.96	22	5.8
Maximum value	34.00	1.04	1.74	2,600	42.00	24.00	1,480	4	34	8.6

Appendix A. The tables above relate to the different certification classes of the EBC. The values in the tables present the heavy metal contents of the produced BMSS and were compared with the limit values for each certification class of the EBC. The red-marked values would not be approved in in the specific certification class, but the green-marked values would. The white boxes are the limit values for Ag, Sn and Bi which are not included in the EBC and therefore not relevant for this study.