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Emission reduction in waste incineration

A comparison of three applicable measures

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Abstract

Emission reduction in waste incineration – A comparison of three applicable measures

Adam Linde

Utilization of waste as fuel for heat and power production is commonplace in Sweden, and the fossil emissions from the incineration of waste is primarily derived from the share of plastics in the fuel. Reducing the share of fossil material in the fuel should therefore lead to diminished local emissions. Alternatively, district heating with waste incineration have potential for implementation of CCS technology, that have the possibility to create negative emissions. The purpose of this study is to evaluate the potential of emission reduction and cost efficiency for three different measures that can be applied for waste incineration: sorting of waste, requirement specification and implementation of CCS technology. This was made with the case of Stockholm Exergi, a district heating actor in the Stockholm region with a desire to achieve emission reduction sufficient to offset additional emissions from as a new waste incineration facility in development.

The measures were compared by constructing distinct scenarios where the emissions and costs of the scenarios could be found in comparison to a reference case where no measures had been applied. For this, modelling of the properties of the waste streams used as fuel was necessary. The results showed that the capacity for sorting is not sufficient to achieve the desired levels of emission reduction on its own, while it is a cost-efficient measure. Requirement specification together with sorting can reduce the emissions to desired levels, but the required reduction of plastics in the fuel is significant. The additional quantities of waste required to produce energy at the same level as before limiting the shares of plastic results in an income from gate fees that mitigate the potential decrease in value of the gate fees brought on by requirement specification. Implementation of CCS technology would create significant negative emissions and yield overall net negative emissions for the studied facilities, but the cost of the technology would create a dependency of external incentives to keep it profitable.

Key words: Waste, Carbon dioxide, Sorting, Requirement Specification, CCS, BECCS

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Sammanfattning

Fjärrvärme som produceras med förbränning av avfall är en betydande del av den svenska energiproduktionen och står för stora utsläpp av koldioxid. Det är även en viktig del av den svenska strategin för hanteringen av det avfall som produceras i samhället. Att använda avfall som bränsle innebär att bränslet är sammansatt av många olika material, där material med fossilt ursprung som plast ger fossila koldioxidutsläpp medan andra material som trä går att betrakta som biomassa. Genom att minska andelen avfall med fossilt ursprung i bränslet kan man därför minska de fossila utsläppen från förbränningen.

En åtgärd som kan appliceras för att minska den fossila andelen är att upprätta sorteringsanläggningar för eftersortering av avfallet, för att minska andelen av oönskade fraktioner innan avfallet går till förbränning. Detta kan göras på exempelvis hushållsavfall efter att det har samlats in till en anläggning för att kompensera för ifall hushållen har begränsade möjligheter till källsortering i hemmet. En annan åtgärd kan istället vara att kravställa hur stor en viss fraktion avfall får vara till leverantörer av avfall. Det avfall som kan kravställas har sitt ursprung i industrin snarare än hos allmänheten och tillhandahålls av avfallsleverantörer.

När avfallets sammansättning förändras, antingen till följd av sortering eller kravställning, ändras även avfallets *”värmevärde”*, mängden energi per ton avfall som förbränns. Detta gör att bränslemängden måste kompenseras för att en förbränningsanläggning ska kunna utvinna rätt mängd energi. I sorteringens fall kan det betyda att avfallet kompenseras med en *”ström”* av avfall med annat ursprung som inte har sorterats, där en avfallsström i denna studie syftar till ett särskilt avfallsbränsle med ett visst ursprung. Därför kan miljövinsterna från sortering bli något förminskade eftersom det kompenserande bränslet kan innehålla plast. I fallet för kravställning kommer det snarare krävas att mängden av det kravställda avfallet ökar för att uppnå den önskade energiproduktionen. Detta kan ge ökade intäkter från mottagningsavgifter för avfall, den avgift som avfallsförbrännaren mottar för att ta emot avfallet. Det är dock mycket troligt att mottagningsavgiften per ton avfall minskar om kravställning gör att leverantören måste anpassa sig till förbrännarens specifikationer.

Ett alternativ till att minska utsläppen är att implementera *”CCS-teknik”*, där CCS står för *Carbon Cature and Storage*. Tekniken syftar till att koldioxid kan avskiljas från rökgasen för att sedan lagras i berggrunden, istället för att släppas ut i atmosfären. Detta skapar då stora utsläppsminskningar och är applicerbart på förbränningsanläggningar för avfall. I de fall då CCS-teknik kan appliceras på biogena bränslen omnämns det som *BECCS*, eller *Bioenergy Carbon Capture and Storage*. Då biogena bränslen med ett organiskt ursprung ses som en del av ett naturligt kretslopp där bränslet tagit upp koldioxid under växtprocessen skapar avskiljning och lagring av biogen koldioxid *”negativa utsläpp”*, i och med att mindre koldioxid släpps ut i atmosfären än vad bränslet tagit upp. Avfall som är en blandning mellan

fossila och biogena material har därmed kapacitet att producera negativa utsläpp beroende på avfallets sammansättning.

Syftet med detta examensarbete är att jämföra potentialen för utsläppsminskning och kostnadseffektiviteten för sortering, kravställning och implementering av CCS-teknik för avfallsförbränning. Arbetet är utfört som en fallstudie på Stockholm Exergi, en fjärrvärmeproducent med avfallsförbränning i Stockholmsregionen. Potentialen för utsläppsminskning bedöms från Stockholm Exergis önskan om att utsläppsminskningar ska kunna väga upp för utsläpp till följd av ett planerat kraftverk med avfallsförbränning i Lövsta. Åtgärderna jämförs i scenarier med ett referensfall där inga åtgärder för att minska utsläppen tagits.

Resultatet visar att sortering av hushållsavfall har en begränsad påverkan på utsläppen, samtidigt som det är en kostnadseffektiv åtgärd eftersom den ökade bränslemängden leder till större intäkter från mottagningsavgifter. Enbart sortering kan dock inte väga upp för utsläppen från det nya kraftverket i Lövsta. Kravställning, tillsammans med sortering, kan skapa utsläppsminskningar som väger upp för Lövsta, dock kvarstår frågan om det är rimligt att anta att det är en gångbar lösning, då plastandelen i det kravställda avfallet som mest får innehålla 5% för vissa strömmar. Intäkterna från mottagningsavgifter ökar i och med att mängden avfall som krävs ökar, samt att utgifter som är relaterade till mängden utsläpp minskar. Ifall det antas att kravställningen kommer att påverka värdet av mottagningsavgifterna ger en grov uppskattning att nettovinsterna för alla anläggningar minskar med mellan 68,9 – 97,1 mSEK. Dock ger scenarierna med kravställing nettointäkter mellan 306,7 – 334,9 mSEK för de studerade anläggningarna innan vinster från energiförsäljning och liknande har räknats med.

För de studerade fallen med CCS uppnås omfattande utsläppsminskningar som ger nettonegativa utsläpp mellan 382 – 119 kton för alla studerade anläggningar. Detta kommer dock med en omfattande kostnad, där det skulle kosta mellan ca 637 – 1545 SEK/ton minskade utsläpp jämfört med om inga utsläppsminskande åtgärder införs. Räknar man med att Stockholm Exergi skulle kunna mottaga incitament för att investera i tekniken skulle det hjälpa, men i vissa fall skulle inte ens det leda till att anläggningarna uppnår betydande nettointäkter. Stockholm Exergi skulle troligtvis bli beroende av att kunna motta incitament för att upprätthålla lönsamhet om de väljer att satsa på CCS-teknik i det här stadiet.

Abbreviations

ar – As received, designation of fuel that has its total weight presented including the weight of the moisture.

B2 – Furnace for waste incineration at the Brista facility.

BECCS – Bioenergy Carbon Capture and Storage, CCS technology applied to bioenergy.

BOSS – Brista One-Stop Solution, sorting facility in Brista.

C&I – Commercial & Industrial, category of waste.

CCS – Carbon Capture and Storage, systems of technologies for capturing carbon dioxide from the source point and storing it geologically.

CHP – Combined Heat and Power, powerplant that produces both heat and power.

CO_2 – Carbon dioxide

ENVIR – Waste treatment company.

EUA – European Union Allowance.

EU-ETS – European Union Emission Trading System.

GHG – Greenhouse Gases.

HSMA – Högdalens Sorterings- och Matavfallsanläggning, sorting facility at Högdalen.

KVV-6 – Closed furnace for fossil incineration at the Värtahamnen facility.

KVV-8 – Furnace for bioenergy at the Värtahamnen facility.

LHV – Lower Heating Value, measurement of energy density in fuel.

MSW – Municipal Solid Waste, category of waste.

NIR – Near Infrared, technology for detecting plastics for sorting operations.

P1-P4 – Furnaces for waste incineration at the Högdelen facility.

P6 – Furnace for waste incineration at the Högdeln facility.

SE – Stockholm Exergi AB, heat and electricity producer in the Stockholm region.

SRF – Solid Recovered Fuel, category of waste.

SVOA – Stockholm Vatten och Avfall AB, waste treatment company in the Stockholm region.

SÖRAB – Waste treatment company.

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1. Introduction

The, by Sweden ratified, *Paris agreement*, states that the global increase in temperature should not exceed 2°C and preferably not 1,5°C (Naturvårdsverket, 2020). The parties included in the agreement are to strive for a balance between emission and absorption of greenhouse gases (GHG) like carbon dioxide (CO_2) for the second half of the 21st century. To keep the agreement, the Swedish government decided on a climate political framework in 2017 stating that Sweden should reach net-zero GHG emissions by 2045, and that negative emissions on a national level should be possible after that (Klimatpolitiska vägvalsutredningen, 2020, pp 25-26). To achieve this, the Swedish GHG emissions would have to decrease by at least 85% compared to the levels of 1990, along with complementary measures to produce negative emissions that would cover for sectors where drastic emission reduction is deemed unlikely (Klimatpolitiska vägvalsutredningen, 2020, p 29).

In Sweden, district heating accounts for a large share of the Swedish energy production, primarily in producing heat and electricity, and in some cases also cold. In 2018, the district heating sector produced a total of 53,7 TWh of heat, delivered to 376 100 subscribers (Energimyndigheten & SCB, p 28). Additionally, the net-production of electricity from district heating was 8,8 TWh, surmounting to approximately 5% of total delivered electrical energy in 2018 (SCB, 2020a). In 2018, the sector for electricity and district heating in Sweden stood for 4 907 kton of CO_2-equivalents, a measure used to compare the climate effect of different GHGs to the equivalent effect CO_2 have. It constituted 9,48% of Sweden's total emissions of approximately 51,8 million ton CO_2-equivalents, making it the 4th most emitting sector after the industry-, internal transport- and agricultural sectors (SCB, 2020b).

Waste is commonly used as fuel in the Swedish district heating industry. Out of the fuels utilized, it had the largest share of fossil emissions the sector made in 2018 with 2 588,8 kton CO_2-equivalents in 2018 (SCB, 2020c). This should be put in perspective to that waste is a heterogenic fuel made up of materials that cause both fossil and biogenic CO_2 emissions. However, district heating companies typically only declare for the fossil share of the emissions made (Gustafsson, 2020a).

In Swedish and European legislations on waste, there is a hierarchy to how waste should be treated or prevented called the "waste hierarchy". In the waste hierarchy, disposal of waste at for example landfills is the least desirable method, while preventing waste generation is the most desirable. (Avfall Sverige, 2020).

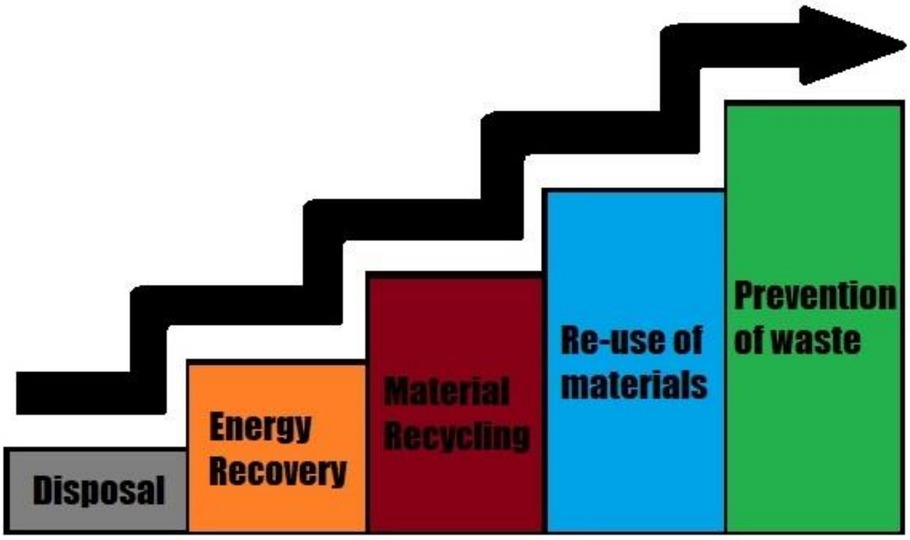

Figure 1: Illustration of the waste hierarchy, in order of least to most desirable treatment of waste.

Even if energy recovery through fuel utilization is the second to last preferable treatment to waste according to the hierarchy, it still plays an important role in treating waste in a safe and efficient way. It is preferable to landfills since waste that is left untreated will produce methane while decomposing (Environmental and socioeconomical impact of landfills, p 40). An alternative for a system where waste is treated in the same country is to export waste, pushing the problem of pollution downstream where the same standards of safety and environmental protection might not exist. Due to many industrialized countries dependance on exporting waste and Chinas import ban of certain waste fractions in 2018, countries in South East Asia have seen an increase in imports of scraps. The waste is treated in an unsafe and sometimes illegal manner where communities are flooded with waste (GAIA, 2019, pp 3-4). A domestic solution to eliminate waste can therefore limit the stress that countries downstream in the international waste trade are put under.

Stockholm Exergi AB (SE) is a Swedish district heating company, co-owned by Fortum AB and the city of Stockholm. They have several plants for waste combustion throughout the Stockholm region (Stockholm Exergi, 2020a,b). The board of Stockholm Exergi decided in December 2019 that their last operational coal powered plant was to be taken out of operation at the end of the operating season for 2019/2020, ending the operation two years earlier than previously planned. The plant, KVV-6, had two furnaces, where one closed in 2019 and the second closed in April 2020. KVV-6 had a total effect of 454 MWh, of which 250 MWh for heat production and 145 MWh for electricity production (Stockholm Exergi, 2019a). The closing approximately halves the CO_2 emissions caused by the company, from between 800-900 kton CO_2 p.a. to an estimated 400 kton CO_2 p.a. (Stockholm Exergi, 2020a). The out-phasing of a coal powered plant is in line with SEs goal to rely on 100% renewable sources of energy, where fossil fuels are to be replaced with renewable energy sources and waste. The loss of production due to KVV-6 closing is planned to be compensated with a new waste incineration plant in Lövsta.

To prevent that the environmental benefit of phasing out fossil fuels could become negated by the fossil emission from the Lövsta plant, Stockholm Exergi took a decision to establish a self-imposed restriction on the amount of CO_2-emissons SE could make annually from its energy production. When the Lövsta-plant is operational, the emission should not exceed the low level that have been reached after the closing of KVV-6. When the Lövsta-plant is operational, by estimation it will increase the amount of waste incinerated annually by about 0,7 million ton. There is no plan to increase the maximum production capacity to levels greater than before non-waste fossil sources were phased out, since the future heat demand is expected to remain at similar levels to today. Incremental improvements to energy efficiency in apartments and offices is calculated to cover the heat demand that an increase in population otherwise would bring (Wickström, 2019).

To achieve this, emission reducing measures of the waste combustion plants would have to be made. This study will examine the case of Stockholm Exergi by comparing three different methods of emission reduction for district heating with waste as fuel: implementing sorting, requirement specification on *"Solid Recovery Fuel"* (SRF), a type of waste fuel with typically high contents of plastic and wood, and implementation of *Carbon Capture and Storage* (CCS), a system of technology and logistics with the purpose of capturing carbon and storing it permanently underground.

1.1 Purpose and questions

This study will examine different measures for fossil emission reduction for district heating actors with waste as fuel. Stockholm Exergi AB will be studied as a case. The examined measures are reducing plastics in the waste through sorting, requirement specification on delivered waste to reduce plastics and thirdly implementing CCS technology on studied plants to create negative emissions. The study will test each measures capability to result in emission reductions great enough to offset the subsequent fossil emissions brought on by the planned facility in Lövsta. The measures will be compared for cost-efficiency in terms of a specific measures cost relative to emission reduction potential.

Following questions will be answered in the report:

- Can the studied measures or a combination of the measures off-set the emissions from the planned facility in Lövsta?
- How should waste content requirement be specified in order to result in emission reduction sufficient to offset Lövsta?
- Which studied scenarios are most cost-effective?

2. Background

Here the background for the concepts and project related to the study is presented. This chapter will both cover the aims for future projects for SE as well as an overview of the technical aspects of the proposed measures.

2.1 Lövsta

The environmental permit application for the Lövsta site was submitted in February 2020 to the Land and Environment Court of Nacka Municipality. An approval of the plans is estimated to take 12 to 15 months. After the permit have been granted the investment decision can be made, which is estimated to be possible in May or June of 2021. If no further delays occur then Lövsta is expected to be online in 2024 (Eriksson, 2020). Further delays could be possible if the legal decision is challenged. The investment decision for the site will be made during 2020 and if no further delays occur Lövsta is expected to be online in 2024.

The plant will have its own harbor and all deliveries of waste to the plant will be made by ship. For this reason, the most suitable source of waste for incineration is deemed to be imported SRF, as fuel deliveries usually made over land as the domestic SRF or MSW would be logistically more difficult (Eriksson, 2019a).

Stockholm Exergi have made some specifications on the acceptable composition on the delivered waste to Lövsta. The share of wood in the composition is required to be of a minimum of 25%. The share of plastics is to be a maximum of 20%, paper can at most constitute 90% of the share. Rubber, textiles, and other combustible waste should be of a maximum of 5% and the share of other non-combustible waste should not exceed 10%. The allowed ash content, i.e the share of the fuel that is left as ash after combustion, is specified to 15%, and the moisture content of the fuel can vary between 17-28%. The range of the lower heating value (LHV) for the boiler, the energy released per combusted quantity of the fuel, is set to 12 to 16 MJ/kg, or approximately 3,3 to 4,4 MWh/ton (Eriksson, 2019b).

2.2 Waste as fuel

When used as a fuel, waste can be defined as heterogenous due to it being a combination of different materials with different properties (WRAP, 2012, p 5). Depending on the material components of the waste, it has a varying share of fossil and biogenic carbon. Materials like plastics, disregarding any biogenically produced plastics, are completely fossil while materials with an organic origin can be regarded as completely biogenic (Bisaillon et al., 2013, pp 67-70). Waste components of a biogenic origin can be regarded as a renewable biomass fuel (Rentizelas, 2013, p 11). Biomass fuels does not increase the amount of CO_2 in the global atmosphere when combusted as the CO_2 emitted during burning can be assumed to be recycled with the growing of the materials they originate from (Caillat & Vakkilainen, 2013, p 198). It is therefore important to be able to determine the share of the waste that have a biogenic origin.

2.2.1 Analyzing the fuel

There are several methods for determining the fossil carbon content of the waste. Picking analysis is the method this study primarily relies on. A picking analysis is conducted by manually sorting a sample of waste from a certain origin into its material components such as paper and plastics, detailing the share the materials have to the total weight of the waste. The results can later be used as input for computations for the share of fossil coal, by attributing each subset to a certain chemical composition (Avfall Sverige Utveckling, 2012, pp 9-10).

Figure 2: Sorting the waste into material components by hand during a conduction of a picking analysis (Vukicevic, 2016)

Another method for analyzing carbon content of waste is flue gas analysis. Samples of the flue gas derived from the waste combustion is analysed for carbon content. (Avfall Sverige Utveckling, 2012, p 6). It can detail the resulting emissions of $CO2$ without it being necessary to know what the fuel consists of. For this study results from flue gas analysis have been used at a few instances as a comparison to the results gained from calculating the chemical composition of the waste derived from picking analysis.

2.3 Sorting fractions of waste

As material recycling is prioritized over energy recovery according to the waste hierarchy, sorting of Municipal Solid Waste (MSW) at a facility is therefore in line with legislative priorities. Stockholm have a tendency to fail at sorting correctly, by estimation only around 7% of plastic packaging from Stockholm municipality in 2016 was able to be materially recycled while the remaining 93% was used for energy recovery (Solis, 2018, p 17). A facility that sorts out plastics from the waste post-collection could therefore sharply improve the recycled amounts.

Sorting out plastics from the fuel could lower the emissions of fossil CO_2 from the energy production if the fuel is not replaced by other fossil sources. It could further have a positive effect if it leads to more plastics being recycled. There is a clear climate benefit if plastics are recycled rather than incinerated. The overall emissions from material rather than energy recovery, factoring in for example emissions derived from producing new material that could otherwise be recycled, are approximately 2,2 kg CO_2e/kg plastic less (Stockholm Stad, 2017, p 24). This study is focused on the local emissions from the studied plants at Stockholm Exergi and do not investigate any effects on global emissions, though it is an important aspect to keep in mind.

There are two technologies for sorting waste relevant to discuss for this study as they are implemented in the sorting facilities this study investigates: optical sorting and utilization of Near Infra-Red (NIR) technology. Optical sorting of waste relies on the households to separate the waste they generate into distinctively colored bags that can then be separated at a sorting facility into each fraction. This method can be applied even if the household has no separate container for the distinctive fractions, i.e most multifamily buildings in Stockholm, as the color identification of the bags allows for the waste to be gathered in larger sacks that can be separated at a facility. Previous implementation of this method in Oslo and Eskilstuna have shown to be less effective in separating each fraction than expected, due to the publics failure to separate the waste into the correct bags. As an example, the plastic fraction was put in the wrong bag to a degree of 28% in Eskilstuna, well above the level of 12% wrongfully sorted that was deemed acceptable (SVOA, 2017, p 5).

NIR is a spectroscopic analysis method that utilizes the vibration of molecular bonds of the material to detect plastics, that can then later be sorted automatically (Xiaoyu et al., 2019, p 3). The plastic can be sorted out as a mixed fraction or into distinct plastic materials like PET. It can be a complement to existing systems for sorting at source and can be combined with an optical sorting system for organic waste (Stockholm Stad, 2017, p 61).

2.3.1 Studied sorting facilities

Stockholm Vatten och Avfall AB (SVOA), a water and waste treatment company, have been constructing a facility for sorting out undesired fractions from the waste in conjunction to SE's Combined Heat and Power (CHP) plant at Högdalen estimated to be operational in 2020 (SVOA, 2017, p 17). The facility, called Högdalens sorting- and food waste facility (HSMA), is designed with two main parts, one for sorting and one for redistributing of pre-sorted food waste from businesses in Stockholm. The sorting only comprises MSW from households and not any Commercial and Industrial waste (C&I). The waste is delivered to the facility in bags, where households are supposed to separate organic waste in green bags and other waste in a different colored bag.

The green bags are first sorted out, whereupon the remaining waste is sorted, utilizing NIR-technology, into four separate fractions: plastics, magnetic metals, non-magnetic metals, and other combustible waste. The successfully sorted fractions destined for material recovery are loaded into containers, while the remaining waste is delivered to SE's combustion plant. The other part of the facility designed for redistribution is of less importance to this report as it services to redistribute solid and fluid food waste from business, which is not of interest for this project (SVOA, 2017, pp 6,16-17).

A study concerning HSMA states that the incoming quantities of waste to HSMA is 134 200 ton/year. It is further stated that the outgoing stream of repackaged organic waste constitutes 17 600 ton/year, and the remaining outgoing stream of MSW destined for energy recovery is 94 100 ton/year (Björnberg, 2018, p 10). The annual cost for HSMA is expected to be approximately 163 mSEK, divided between 74,3 mSEK in operational costs and 91,9 mSEK in capital investment cost. The annual profit from recovered materials is expected to be 10,3 mSEK, resulting in a net cost of 155,9 mSEK/year. The whole cost, investment and operational, of HSMA is paid for by SVOA (Folkesson, 2020).

Brista One Stop Solution (BOSS) is a sorting facility, jointly constructed by Stockholm Exergi and the waste treatment company SÖRAB. It is designed to separate plastics and metals from the household waste before it is used as fuel at the Brista plant. By estimation the facility will be able to sort out approximately 18 kton plastics and 2,5 kton metals yearly. The facility will utilize NIR technology to sort out plastics and an eddy-current separator to sort out metal. The total investment cost for BOSS was 380 mSEK, though the project received investment support of 134 mSEK (Bioenergi, 2019). The annual operational costs for BOSS are estimated to be 18,4 mSEK (Gustafsson, 2020b).

2.4 Requirement specification

For the purposes of this study, the term "requirement specification" of the fuel is defined as the waste treatment actor placing specific requirements on the constitution of the waste used as fuel on the delivering partner to restrict the fossil CO_2 emitted from combustion of the waste. The process of placing demands on the content of the waste is nothing new and is done to some degree by Stockholm Exergi already to ensure certain qualities of the fuel (Stockholm Exergi, 2018, p 20). To fulfill the requirements on emissions investigated in this report, a much stricter limitation on the fuel than what has previously been done is required, why it is useful to define requirement specification as a separate term for it.

From interviews with actors such as waste generators from civil society and industry, agencies and interest groups made by Avfall Sverige in 2017, many actors request that producers of district heating should put higher demands on the waste they use as fuel, as this could put pressure on municipalities and such to improve their waste treatment practices to prohibit that waste is generated (Eneqvist et al., 2017). This study does not investigate the impact the studied measures could have on reducing the quantities of waste that is being generated by society.

2.5 Carbon capture and storage

CCS technology when it is applied to bioenergy is called BECCS, Bioenergy with carbon capture and storage. BECCS exploit the ability of biomass to absorb CO_2 when growing. When the biomass is then incinerated in a facility with CCS-technology, the CO_2 is captured and stored geologically. Even if it makes no difference for the atmospheres ability to trap heat whether the CO_2 is fossil or biogenic, captured biogenic CO_2 can achieve a global "net negative emission", due to that it is CO_2 from a renewable cycle that has been removed (Fridahl, 2018, p 1).

In contrast to lowering emissions through changing the constitution of the fuel by means of sorting or requirement specification, carbon capture and storage (CCS) technology allows for capture of CO_2 at the source of emission, separating CO_2 from the flue gas and storing it permanently underground (SGU, 2020). A global emission reduction is not given for either sorting or requirement specification, as the excluded plastics must have an alternative disposal other than incineration at SE's facilities. If the excluded plastic is unable to be recycled, it is reasonable to assume that it would be incinerated elsewhere. CCS on waste fuel therefore provides an end state of the plastic that guarantees that it will not be incinerated or put in a landfill downstream. In a broader perspective, if society strives for net-zero emissions then no fossil plastics could be incinerated. Application of CCS technology on facilities for waste incineration could be a strategy to eliminate plastics that is deemed necessary, like medical equipment, as well to cover for the predictable outcome that achieving a society wide elimination of 100% of all fossil plastics could be impossible (Gustafsson, 2018, pp 71, 78).

For the case of applying CCS-technology for a waste incineration facility, the emission reduction can be counted for in two ways. Since the waste is a heterogenous mix of fossil and biogenic material, the emissions would be partly of fossil and biogenic CO_2. Captured fossil CO_2 would reduce emissions to the extent that the fossil CO_2 was able to be captured from the flue gas. As the biogenic CO_2 emissions does not count for any fossil emission, the captured biogenic CO_2 would instead be counted as negative emissions.

Other than for CHP-plants, BECCS technology can be utilized for pulp and paper facilities and facilities for bioethanol production (Arbman Hansing & Fridahl, 2018, pp 31-32). There is high potential for BECCS in Sweden if those other applications are accounted for, which could possibly be beneficial to development of shared infrastructure of storage.

2.5.1 Cost for CCS

To estimate the cost of implementing CCS-technology on a plant, three distinct costs needs to be considered: the cost for capture, cost for transport and the cost for storage.

The cost for capture is related to the volumes of CO_2 that the plant can capture. The cost for a plant increases if the plant is designed to capture a greater amount of CO_2, but it is mainly the operational costs that increases while the investment costs remain on a similar level as if the plant was designed for lower concentrations and volumes of CO_2. This results in that the relative cost per captured ton of CO_2 is lower for a plant designed for larger volumes than a plant designed for smaller volumes (Klimatpolitiska vägvalsutredningen, 2020, p 358).

The infrastructure for transportation of captured CO_2 could either be with pipelines or by ship. Though transport by pipeline is more cost efficient if the distance to storage is short, transportation by ship have some advantages to a CCS system under construction. Future storage locations will probably be constructed beneath the sea floor, leading to generally long transport distances from Swedish plants, making transport by ship more beneficial to pipelines. Transportation by ship is more flexible to the quantity of captured CO_2 it can transport, which is important in the developing phase of a national CCS system when there is some uncertainty to the volumes being captured (Klimatpolitiska vägvalsutredningen, 2020, pp 363-364). The investment cost for transport is a more significant part of the total cost for CCS when the system is not fully expanded and could be of similar size to investment cost for capture. When the system has been developed further, there is a possibility for adjacent actors to share infrastructure for transport and storage and the costs for transport are proportionally smaller to the cost for capture (Klimatpolitiska vägvalsutredningen, 2020, p 365).

Site specific parameters, like storage capacity and geographic location, have a great effect on the costs for storage. These parameters are normally unknown or assessed with great uncertainty, deeming the task of estimating a cost for storage difficult. A good estimation of the cost requires knowledge of the storage site. In a study made on several potential sites in Scandinavia, Utsira in Norway was found to result in the lowest cost, €7/ton CO_2. A Swedish comparable site for storage, Faludden, was estimated to cost €16/ton CO_2. Since costs for transport by ship increases slow with a greater distance while the difference of cost for storage could be great between different sites, the total cost for transport and storage could be lower with a storage site in Norway rather than a Swedish site. There are therefore some advantages of scalability with a shared Nordic storage site in the Norwegian North Sea, being economically efficient.

A governmental investigation put forward what measures should be taken to support the development of BECCS. It suggests that the measure the Swedish government should take to guarantee an income for negative emissions with BECCS is reverse auctioning. In a reverse auction, the BECCS actors bid on a contract for capturing and storing a certain quantity of CO_2. The winner of the auction will usually be the actor that can provide the service to the lowest price, minimizing the cost for the government. The paid sum to the negative emission provider will be the difference between the agreed guarantee price and any other funding, such as funding from the EU or an income from a market for trading negative emission credits. A requirement for an actor to be eligible to receive payment through a reverse auction is that applications for relevant support from the EU have been made (Klimatpolitiska vägvalsutredningen, 2020, p 105).

3. Method and data

The chapters dedicated to method and data have been combined for this paper, due to their interrelationship with each other and that some methods are difficult to explain in general terms without the relation to the actual data that have been used for the calculations.

3.1 Scenarios

The effect of each measure is compared by constructing distinct scenarios where the measures are applied in combination or individually. The measures applied in each scenario can be seen in table 1 below.

Table 1: Measures utilized for every scenario. The applied measures for the scenario are marked by checkmarks in respective column.

Scenario	Planned sorting	Extended sorting	Requirement specification on SRF	CCS on KVV-8	CCS on Lövsta
Reference case					
1.1 Only planned sorting	✓				
1.2 Extended sorting	✓	✓			
2.1 Requirement specification on SRF	✓		✓		
2.2 Requirement specification on SRF + extended sorting	✓	✓	✓		
3.1 CCS on KVV-8	✓			✓	
3.2 CCS on Lövsta	✓				✓

3.1.1 Reference case

Albeit not a studied scenario, calculations are made for the case where no measures are taken for reducing the fossil CO_2 emissions from the studied plants. This acts as a reference for the magnitude of the emission reduction for the other scenarios. This case is not likely to reflect reality since the sorting facilities studied in scenario 1.1 is already decided on.

3.1.2 Scenario 1.1

The first scenario represent what definitive efforts for emission reduction that has already been decided on though not yet realized, as it investigates the potential for reducing CO_2 emissions with the measures that is already planned for and that will be in place in 2024 when Lövsta is estimated to be operational. The measures refer to the sorting facilities HSMA and BOSS at Högdalen and Brista respectively, where the sorting facilities will have the sorting capacity discussed in 2.3.1. All further scenarios are designed to have the emission reduction from the planned sorting facilities as a base for aggregated emission reduction, since it is reasonable to assume that they will be in use regardless of further measures taken.

3.1.3 Scenario 1.2

This scenario investigates the potential for extended sorting at the Högdalen site. The scenario imagines if a second facility of equal size to HSMA would be operational at Högdalen, increasing the capacity for sorting waste twofold at Högdalen. Further increase of the sorting capacity than that is not investigated, since the capacity of four or more sorting facilities of that size would exceed the quantities of waste incoming to Högdalen and Brista combined. Neither is the construction of a lower capacity facility investigated, due to lack of knowledge of the cost for a facility designed for a different capacity.

3.1.4 Scenario 2.1

Here the aggregated emission reduction from planned sorting alongside requirement specification of the fuel streams with SRF waste used in P6 and Lövsta. Since this investigation includes combining different constitutions of fuel at different plants this yields many combinations for how effective the measures are at reducing emissions. The method for finding the combination of requirement specified fuel at the different plants (along with the reductions due to sorting) is specified further in 3.4.3.

3.1.5 Scenario 2.2

This scenario represents if SE would implement specifications on the fuel as in scenario 2.1 as well as an extended sorting as in scenario 1.2.

3.1.6 Scenario 3.1

Here the estimated potential of negative emissions and the estimated cost for implementation of carbon capture technology on the KVV-8 plant are compared with the calculations on CO_2 emissions made for this report. The estimations for the KVV-8 plant are gathered from a previous study (Lehvin, et al., 2019). The transport of captured CO_2 is assumed to be by ship.

3.1.7 Scenario 3.2

Similarly to scenario 3.1, this scenario investigates the effects of implementing CCS on the Lövsta plant. The method for calculating the negative emissions from such a plant is specified in 3.4.4. As Lövsta is designed with a port for the import of waste, it is also assumed that transport of captured CO_2 will be by ship.

3.2 Streams of waste

Waste is a heterogenic fuel and to determine the composition of the waste a degree of simplification is necessary. For this study, nine different fractions of waste were chosen to represent the composition of waste to an accurate degree. The fractions chosen were plastics, wood, organic material, paper, metal, rubber, textile, combustible waste and non-combustible waste. These categories were chosen due to their representation in most of the picking analyses for the fractions discussed below.

3.2.1 Fractions, compositions and streams

This study refers to waste in a series of distinct ways and for clarity follows a definition of the terms used. Firstly, the waste is made up of different fractions of waste. A fraction refers to the relative mass of a material in a composition of waste. The fractions used in this study are plastics, wood, organic material, paper, metal, rubber, textile, combustible waste and non-combustible waste. The sum of all fractions makes up the composition of the waste. The composition therefore refers to what the waste is made up of. The composition has a set of properties related to the fractions: fossil carbon share, moisture level and heating value.

A stream of waste is defined, for this study, as a composition with a certain quantity of waste. It is used for the calculations of CO_2 emissions and costs and incomes related to the quantities of waste. A composition can make up multiple streams, as for example the streams for MSW in Högdalen and Brista both uses the composition for MSW to explain its related properties, but they have distinct quantities and other factors may differ. The quantity of a stream is given by its related energy quantity and the heating value for the composition used, as detailed in chapter 3.3.6.

3.2.2 Composition of Swedish MSW

The analysis relied on three reports detailing picking analysis conducted on waste from the greater Stockholm region. Two of the studies was made on behest of Stockholm Vatten by two different consulting firms, by Atkins in 2015 and by Sweco in 2016. These reports presented the data in a way directly comparable to each other. The third report, conducted by SÖRAB in 2016, presented its findings in a different way to the previous two. Thus, the data set required some minor recalculation for it to be comparable to the other two, possibly leading to some degree of error, though with its sample size much larger than the others it was still of relevance to this study. From the composition of waste presented in the reports, the percentages of the waste as received was grouped into the nine fractions described in 3.2.1.

The data set from the Atkins and Sweco reports yielded one set of composition each while the SÖRAB report yielded two sets, one for the composition of combustible waste from single family residential buildings and one composition for multiple family residential buildings. The compositions for the data sets as well as for a weighted arithmetic mean value for all sets is detailed in figure 3.

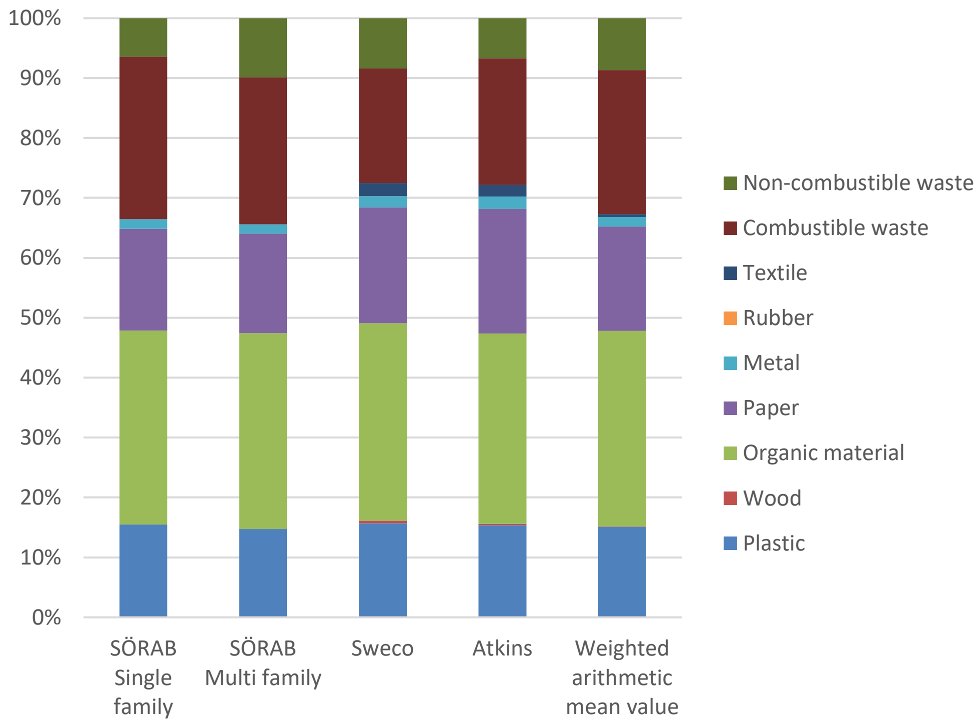

Figure 3: Composition of MSW from different picking analyzes and the weighted arithmetic mean value derived from the data and used to represent the composition of MSW in this study (Lundin, 2016, Vukicevic, 2016, Silferduk et al., 2017).

The weighted arithmetic mean value for the composition was calculated to yield a composition as representative of the Stockholm region as possible. The weights regarded the sample size of the analysis, representation of single- or multifamily residential buildings in the original reports, as well as assessed uncertainty from the data. The sample sizes of combustible waste from the SÖRAB report dwarfed the other two, with 25 320 kg for single family residents and 26 610 kg for multifamily, compared to Atkins 3 680 kg and Sweco’s 6 660 kg. Therefore, the SÖRAB data sets are more heavily weighted than the others.

The weight factor is designed to reflect the living conditions in the Stockholm region, where single family residents compose approximately 25% and multifamily residents approximately 66% of all residents (SCB, 2019). Simplifying by ignoring the remaining 9% share of unspecified residency, the factor was calculated by multiplying the share of single family waste by 0,3 and the share of multifamily waste by 0,7. This yields a comparably greater weight to the single family residents, which can be motivated by the fact that single family residences yields a greater share of waste per residences. Finally the uncertainty factor was designed to take into considerations the uncertainty derived from adjusting the data from the SÖRAB report to be comparable to the other two, to account for possible rounding errors. The SÖRAB report did not provide data on the amount of wood and textile constituting the composition, giving misleading amounts in the arithmetic mean fractions. The missing fractions are likely a reason for the greater amount of "combustible waste" in the SÖRAB data set. The weight factor for the uncertainty was set to 0,8. The resulting weight is determined by multiplying each of the factors. Even though the reports dates back a few years, the data was assumed to accurately represent the current composition of MSW waste.

Table 2: Factors for establishing the weight for each data set for the arithmetic mean value of the MSW composition.

Data set	Uncertainty factor	Sample size factor	Single-/multifamily factor	Resulting weight
SÖRAB Single family	0,8	0,41	0,3	0,0984
SÖRAB Multifamily	0,8	0,43	0,7	0,2408
Atkins	1	0,11	0,62	0,0682
Sweco	1	0,06	0,52	0,0312

With the resulting weight for each data set, the arithmetic mean value for the fractions of waste can be established, as presented in table 2, with the equation

$$wt_{ar,i,arithmetic} = \frac{\sum(wt_{ar,i,j} * F_{weight,j})}{\sum F_{weight,j}}, \qquad (1)$$

where $F_{weight,j}$ is the resulting weight for data set j, and $wt_{ar,i,arithmetic}$ and $wt_{ar,i,j}$ are the arithmetic *weight ton* for the *as received* (ar) fraction i and the weight ton of fraction i from data set j respectively. ar refers to when the composition of the waste includes moisture (see 3.2.6 for further details). Weight ton is a unit expressed in kg/100kg, and is used to express a fraction of waste as a share of the total weight. Further, in this paper, $wt_{ar,i,arithmetic}$ will simply be referred to as $wt_{ar,i}$, the weight ton for a fraction of MSW in ar as the arithmetic value is used to represent the composition of MSW.

3.2.3 Composition of imported SRF

The shares for the imported SRF, used at the P6 plant in Högdalen together with Swedish SRF, are gathered from an analysis made on imported waste from GemUK in Great Britain made in 2018 to 2019. The composition is assumed to be representable for imported industrial waste with other origins.

3.2.4 Composition of Swedish SRF

Data for the composition of Swedish SRF was gathered from the same analysis as the imported SRF, with waste delivered to the P6 plant from four different suppliers. A weighted mean value was calculated to take into consideration that the volumes of waste delivered from the different companies varied, giving the mean value a representation of how large a share of the total amount of waste each supplier contributed with. The data set can be seen in figure 5 in chapter 4.1.1.

3.2.5 Composition of C&I waste

There is a lack of picking analyses made on determining the composition of the C&I, complicating an accurate determination of the composition of the fuel. From chemical analysis made on the flue gas with varying amounts of C&I mixed in with municipal waste, the results show that the amount of fossil coal in the mix varies to just a small degree to household waste, even with as much as 70% C&I mixed in. For this reason, this paper considers it feasible to approximate the C&I with household waste. This however should be noted as a significant source of error for determining a representable LHV and for estimating the CO_2 emissions caused from combustion of this stream.

3.2.6 Moisture content and the dry composition

It is important to know whether the composition of the waste given by the picking analysis expresses the waste in a dry composition or in ar. If the analysis is made on wet waste, the composition is in ar. If the waste has been dried before the analysis is made, it is then expressed in dry. This affects the relative share of the waste regarding the content of moisture that can be expected. Different fractions of waste generally hold different amounts of moisture, thus a fraction that holds a great amount of moisture would represent a larger share in the composition in an as received composition than it would in a dry composition.

In this study, the dry composition of the waste is used to calculate the heating value. In the cases where a composition was given in ar, the composition in dry was calculated utilizing the moisture content per fraction given in tables 3-4. To find the moisture content of a composition and to convert a wet composition to dry, the first step required is to find the dry weight of the individual fractions. The dry weight of the composition, wt_{dry}, is then the sum of the individual weights of the fractions in ar, $wt_{ar,i}$, minus the moisture content of each fraction, M_i, where i denotes the fractions. This presents in eq. 2 as

$$wt_{dry} = \sum wt_{ar,i} * (1 - M_i). \tag{2}$$

The moisture content for the composition can then be established as

$$M = \frac{wt_{ar} - wt_{dry}}{wt_{ar}}. \tag{3}$$

Since the general data for the elemental share of each fraction is given in % of dry, it is necessary to find the dry composition of the waste if it is given in ar to be able to find the elemental composition of the fuel required for calculating the LVH, described in 3.3.1. A wet composition can be converted by dividing the individual dry weight of each fraction with the total dry weight, as in

$$wt_{dry,i} = \frac{wt_{ar,i} * (1 - M_i)}{wt_{dry}} * 100, \tag{4}$$

where $wt_{dry,i}$ is the weight ton for the individual fraction i. This will yield a composition of the waste where no moisture is included and the weights of the included fractions, given in kg/100 kg, should summarize to 100 kg for all fractions.

To find the weight in ar from a composition given in dry is not necessary for calculating the heating value with the method used in this study. However, if a picking analysis expresses the composition of the waste in dry, finding the wet composition is useful to determine the relative sizes of each fraction when it is delivered. In this study, a central focus is whether desired levels of CO_2 emissions can be achieved cost efficiently by requirement specification on the waste from a supplier, limiting fractions like plastics to a determined share of the total composition. Therefore, it is necessary to know the composition in ar, as the waste typically holds moisture when delivered, thus the specification of the fuel will be made on the wet basis. This gives the following

$$wt_{ar} = \sum \frac{wt_{dry,i}}{(1 - M_i)}. \tag{5}$$

The moisture content can be found with equation 3, though in this case the dry weight is 100 kg and the ar weight will typically be more than 100, as the factor with the moisture content is in the denominator rather than in the numerator. The weight ton for the individual fraction in ar can then be found with

$$wt_{ar,i} = \frac{wt_{dry,i}}{(1 - M_i) * wt_{ar}} * 100, \tag{6}$$

which will similarly to equation 4 give a composition which will summarize to 100 kg, but including moisture in each fraction, giving different relative sizes of each fraction than the dry composition.

3.2.7 Adjustments of streams to sorting and requirement specification

A vital part of this study is to find the potential for reduction of CO_2 from waste sorting facilities or requirement specification for limited plastic fractions in the SRF waste. To find the compositions of waste that would be representative for these measures, they are derived from the existing streams they would replace.

Two different streams of waste are required to simulate the changed composition of the fuel after the waste have been sorted in the facilities in Högdalen or Brista. Both streams have the generalized MSW waste composition as a template, and that composition is modified to the sorting facilities specific sorting capabilities.

When portions of the fuel are sorted out the relative shares of the fractions of waste will change, since not all fractions are sorted and the rate to which the materials are sorted differs from each material. To find how the composition changes, the first step is to find how each fraction diminishes individually. This is found with

$$wt_{ar,i,sorted} = wt_{ar,i} * (1 - r_i), \tag{7}$$

where $wt_{ar,i,sorted}$ is the weight ton in ar of fraction i when a portion of the fraction have been sorted out, and r_i is the sorting rate of the fraction. Each fraction is given in kg/100kg, meaning that of 100 kg of waste, a percentage of the weight will be of a certain fraction. If a fraction is altered, this will change the weight proportion of the composition. If for example the fraction for plastics is reduced by 75%, this does not mean that the share of plastics in the whole composition will be 75% less, since the total weight of the composition will have diminished. Therefore, it is important to adjust the share of each fraction to the percentage of the new total weight. The new weight ton of the sorted fraction, $wt_{ar,sorted}$, is found with

$$wt_{ar,sorted} = \frac{wt_{ar,i,sorted}}{\sum wt_{ar,i,sorted}} * 100. \tag{8}$$

This gives the new share each fraction holds relative to 100kg of waste. The new composition can then be used to determine heating value and CO_2 emissions. The factor of the waste that is not sorted out, $F_{remaining}$, can then be used to find the quantity of the waste that will be used as fuel, relative to the capacity of the sorting facility. This factor is found with

$$F_{remaing} = \frac{\sum wt_{ar,i,sorted}}{100}. \tag{9}$$

The next important step is to find the sorting rates of the fractions that should be sorted out. The unknown sorting rate in this case is the sorting rate for organic waste, $r_{organic}$. This rate can be found from knowing the capacity of the facility, in equations denoted as $m_{capacity}$, and the specific quantity of how much organic waste that should be separated.

As discussed in 2.3.1, we know that of a capacity for sorting of 134 kton for HSMA at Högdalen, 17 600 tons of organic waste will be redistributed from the incoming stream of MSW. 17 600 tons of organic waste is estimated to be separated from the total quantity of organic waste in the incoming stream, $m_{organic}$. We find first $m_{organic}$ from the weight ton for the organic waste in ar for the composition, $wt_{ar,organic}$, and then the specific sorting rate for organic waste at HSMA by

$$m_{organic} = m_{capacity} * \frac{wt_{ar,organic}}{100}, \tag{10}$$

$$r_{organic,HSMA} = \frac{17600}{m_{organic}}. \tag{11}$$

As with HSMA, the sorting rate of organic waste for the BOSS facility at Brista is not known but can be found with the same method. The capacity to separate organic waste from the fuel is estimated to be less than in HSMA, to the capacity of 10 000 ton/year. The capacity for BOSS is otherwise assumed to be the same as for HSMA. This gives us

$$r_{organic,BOSS} = \frac{10000}{m_{organic}}. \tag{12}$$

To find the requirement specified streams, a similar method as for finding the sorted streams are used. A maximum value for the plastic fraction is set and the fraction is then reduced with the same method as of eq 7 and recalculated with eq 8 so that the share of the limited fraction is less than the maximum allowed value given in ar.

In contrast to the sorting, the template streams are the imported and Swedish SRF streams that are given in dry. Before the reduction of the fractions are made, the stream is transformed into an ar composition. This is necessary to find how large the shares of the fractions would be when delivered. The stream can then be transformed back into dry.

The maximum levels of plastics were chosen with a 5-percentage interval. The stream with the most plastic was designed to allow for less than 20% plastics, while the other streams contained less than 15%, 10%, 5% and 0% plastics. A stream was designed to fulfill the conditions set by the fuel specification of the Lövsta facility. For this stream, textile was limited to fall below a 5% share of the total weight. For simplicity, this condition was utilized for all designed streams of imported SRF waste.

3.3 Properties of the streams

This chapter will show where these inputs were found and show how they were applied to find the variables useful for this study.

3.3.1 Calculating LHV

The shares of elemental components the material affects the LHV of the fuel in different ways. The content of carbon in the fuel is important for a higher LHV, as well as the content of hydrogen, while the share of oxygen in the material along with moisture content gives a lower value. Some elements generally make out a small amount of the total composition of the elements of a material and thus have a smaller impact on the heating value. An equation for the lower heating value can be expressed as

$$LHV = 34{,}1 * \gamma_C + 102 * \gamma_H + 6{,}3 * \gamma_N + 19{,}1 * \gamma_S - 9{,}85 * \gamma_O - 2{,}5 * M, \qquad (13)$$

where γ_C, γ_H, γ_N, γ_S, and γ_O denotes the shares of carbon, hydrogen, nitrogen, sulfur and oxygen respectively of the fuel. (Mörtstedt & Hellsten, 1999, p 21). This yield the LHV expressed in MJ/kg. In this report, the unit used for LHV is MWh/ton, thus the LHV must be converted. This is made by dividing the value in MJ/kg by 3,6. Whenever the values of the streams LHV is mentioned in this report, it refers to the value expressed in MWh/ton.

3.3.2 Elemental components for fractions of waste

Elemental analysis for each fraction of waste studied in this report has a specific composition of elements, a general moisture content for the material as received to the power plant and a share of ash that the fraction will leave behind when combusted. Note that non-combustable fractions such as metal yield a 100% share of ash, since this analysis shows the properties of the fuel while combusted. Tables 3 – 4 shows the elemental properties of the fractions included in this study.

Table 3: The elemental properties as well as moisture- and ash content for the waste fractions for plastic, wood, biological waste and paper. Moisture content given in % of ar, while all other factors are given in % of dry (Bisaillson et al., 2013).

Content	Plastic (%)	Wood (%)	Organic waste (%)	Paper (%)
Moisture	30	13	65	35
Fossil carbon	73	0	0	0
Biogenic carbon	0	43	47	44
Total carbon	73	43	47	44
Hydrogen	12,0	5,3	5,8	6,4
Oxygen	5	37	29	44
Nitrogen	0,3	1,9	3,2	0,3
Sulphur	0,15	0,15	0,22	0,12
Ash	7	12	12	5

Table 4: The elemental properties as well as moisture- and ash content for the waste fractions for metal, rubber, textile, combustible waste and non-combustable waste. Moisture content given in % of ar, while all other factors are given in % of dry (Bisaillson et al., 2013).

Content	Metal (%)	Rubber (%)	Textile (%)	Combustible waste (%)	Non-combustable waste (%)
Moisture	35	8	10	34	24
Fossil carbon	0	58	0	3	0
Biogenic carbon	0	0	55	45	0
Total carbon	0	58	55	48	0
Hydrogen	0	8,9	6,6	6,0	0
Oxygen	0	11	31	38	0
Nitrogen	0	8,7	4,1	0,2	0
Sulphur	0	1,10	0,10	0,10	0
Ash	100	10	2	8	100

To determine LHV, it is not necessary to know the share of fossil and biogenic carbon, only the total amount of carbon. This distinction becomes important for analysis of CO_2 emission, detailed later in this study.

3.3.3 Input energy quantity per plant

To model the correct quantities of fuel and as a consequence the fossil emissions associated with each stream, two input variables was necessary to find: the input energy quantity of the plant and the initial estimation of the fuel quantity of the streams.

An internally made estimation of the energy quantities for the plants discussed in this study, detailed in table 5, shows the total energy quantity that all streams of waste should account to at a certain plant. The estimation was made for 2024 and includes the contribution from Lövsta.

Table 5: Energy quantities and included streams related to each plant (Sandberg, 2019).

Plant	Energy quantity (GWh)	Streams included
P1-P4	1539	MSW+C&I
P6	635	SRF+Imported SRF
B2	590	MSW+Imported MSW+C&I
Lövsta	2014	Imported SRF

Only the Lövsta plant have a single stream giving cause to the related energy quantity. For the other plants, where multiple streams combine to a plant total energy quantity, it is important to find a way to estimate how the energy quantity is divided among the streams.

3.3.4 Initial estimation of the quantities of streams

The 2018 quantities of fuel for each stream was used as historical data to estimate the energy quantities of the streams.

Table 6: values for the quantities of the streams of the 2018 levels, expressed in kton (Olofsson, 2019)

Stream (kton)	P1-P4	B2	P6
MSW	400	70	-
Imported MSW	-	30	-
C&I	100	94	-
SRF	-	-	162
Imported SRF	-	-	42

To further emphasize the distribution of the streams of waste used for the plants in this year, table 7 shows that distribution. This is found by dividing the historical quantity for the stream as of table 6, with the quantity of all streams of that plant.

Table 7: The share of each stream of the total quantity of waste used as fuel for a given plant.

Share of stream	P1-P4 (%)	B2 (%)	P6 (%)
MSW	80	36	-
Imported MSW	-	15	-
C&I	20	48	-
SRF	-	-	79
Imported SRF	-	-	21

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3.3.5 Energy quantity adjusted to share of waste

To find the specific energy quantity of a stream, the shares of the streams as of table 7 is used to find the distribution of the energy quantity of the plant total to the specific streams. The total energy quantity of the plant as in table 5 was multiplied to the corresponding shares as

$$Q_i = Q_j * \frac{m_i}{m_j}, \qquad (14)$$

where Q_i and Q_j refers to the energy quantities related to stream *i* and plant *j* respectively, and m_i and m_j are the quantities of the historical fuel data for stream *i* and plant *j*.

As the quantity of energy is related to the specific heating value a stream hold, it should be noted that this only gives a rough estimation of the quantity of energy a specific stream can be expected to hold. Nonetheless it allows for further calculation with the individual heating values calculated for the streams in this report.

Table 8: Adjusted quantities of energy related to each stream.

Plant	Stream	Energy quantity (MWh)
P1-P4	MSW	1231
	C&I	308
P6	SRF	470
	Imported SRF	165
B2	MSW	213
	Imported MSW	91
	C&I	286
Lövsta	Imported SRF	2014

With the specific heating values of the streams and the adjusted energy quantities as of table 8, the quantities of waste suitable to the conditions of this study can be calculated.

3.3.6 Size of the streams

The last important property of the streams relevant to this study is the size of the stream, the amount of waste that can be used as fuel. The mass of the waste was determined by its relationship to the energy quantity design parameter of the stream and the calculated LHV of the stream. This can be expressed as

$$m_i = \frac{Q_i}{LHV_i}, \qquad (15)$$

where mi, Q_i, and LHV_i refers to the quantity of fuel, the related energy quantity and the LHV of stream i. This relationship yields a value of the quantities of the streams that is derived from the specific heating values that have been calculated from the contents of the waste, and should represent an the relationship between the energy derived from the waste and the constitution of the streams better than utilizing historical data for the amounts of waste. For the streams unrelated to the studied sorting practices and the quantities of the MSW waste before sorting, this yields a finished value that can be used for the calculations of CO_2 emissions and costs and incomes related to the quantities of waste.

3.3.7 Determining the quantities of the sorted streams

To determine the quantities after sorting, some extra steps is necessary to take. The first step is to determine the quantity of the MSW that is initially received to the facility, $m_{incoming}$, calculated with equation 15 utilizing the energy quantities for the P1-P4 and B2 facilities detailed in table 8 and the LHV for the original MSW composition as in figure 7. The capacities for the sorting facilities are set to 134,2 kton for the case with already planned sorting. For the extended scenario, the capacity for Högdalen is twice as high at 268,4 kton, as the scenario imagines an extra sorting facility of equal size of the original, while the capacity for Brista remains at 134,2 kton. The surplus or shortfall (expressed as negative surplus) of waste to fill the capacity, $m_{surplus}$, is determined by

$$m_{surplus} = m_{incoming} - m_{capacity}, \quad (16)$$

and can be seen in table 9 below.

Table 9: Initial quantities of waste before sorting and surplus of unsorted waste after filling the capacities of the sorting facilities, rounded down to kton of waste.

Stream	Quantity (kton)	Surplus of sorting capacity (kton)
MSW P1-P4	441	307
MSW P1-P4 extended sorting	441	172
MSW Brista	76	-57

As the initial quantity of fuel for the Brista facility is not enough to utilize the sorting facilities capacity to its full extent, a portion of the surplus from Högdalen is assumed to be redistributed to cover the remainder of the capacity in Brista. The remainder of the surplus after redistribution represent the quantity of the waste that will not undergo any sorting. We get the following relationships

$$m_{surplus,B2} = -m_{redistributed,P1-P4}, \quad (17)$$

$$m_{unsorted,P1-P4} = m_{surplus.P1-P4} - m_{redistributed,P1-P4}, \quad (18)$$

$$m_{unsorted,B2} = m_{surplus,B2} + m_{redistributed,P1-P4}, \quad (19)$$

where $m_{surplus,B2}$ and $m_{surplus,P1-P4}$ is the surplus from B2 at Brista and P1-P4 at Högdalen, $m_{redistributed,P1-P4}$ is the quantity of the waste that is redistributed from P1-P4 to B2, and $m_{unsorted,P1-P4}$ and $m_{unsorted,B2}$ is the quantity of the waste at P1-P4 and B2 that is left of the initial waste stream after the capacity of the sorting facilities have been filled.

When some of the material is sorted out of the stream the quantity of the waste will change again. As described by equation 9, the factor for the remaining waste gives how much of the sorted stream that is left to be used as fuel. With the quantity of the waste that will undergo sorting equal to the capacity of the sorting facility, this gives us the relationship below.

$$m_{sorted} = m_{capacity} * F_{remaining}, \quad (20)$$

$$m_{separated} = m_{capacity} - m_{sorted}, \quad (21)$$

where m_{sorted} is the remaining quantity of waste that has undergone sorting, and $m_{separated}$ is the quantity of the waste that have been sorted out from the fuel stream.

The difference between m_{sorted} and $m_{separated}$ should be noted, as well as the differences of both quantities to the $m_{unsorted}$ quantity. While m_{sorted} is the part of the sorted waste stream that is left after sorting and subsequently used as fuel, it is attributed with the specific composition and LHV related to the sorting. $m_{separated}$ is what is discarded from the stream and is only of interest for this report in terms of income calculation, further detailed in 3.5.1. $m_{unsorted}$ refers to the quantity of waste that were part of the surplus of waste that remained after the sorting capacity is filled.

The loss of waste that can be used as fuel and the lower heating value for the sorted stream results in a drop in energy quantity for the streams. To keep consistency in the power output of the plants, it is assumed that the loss of energy quantity can be compensated with additional C&I waste that is assumed to not undergo sorting. To determine the quantities of waste needed for compensation, the energy content for the streams after sorting should be compared to the initial energy content of the incoming waste as

$$Q_{uncompensated} = Q_{unsorted} + Q_{sorted} + Q_{C\&I,initial}, \tag{22}$$

where $Q_{uncompensated}$, $Q_{unsorted}$, Q_{sorted} and $Q_{C\&I,initial}$ are the energy quantities for all streams before compensation, the unsorted stream, the sorted stream and the intital C&I stream respectively. All energy quantities can be found with the relationship from equation 15 by utilizing the corresponding quantites of waste.

To find the quantity of C&I waste fuel needed for the compensation, $m_{C\&I,compensation}$, find the difference between the intitial energy quantity before any waste have been sorted or compensated ($Q_{initial}$) and the energy quantity after sorting, and divide with the LHV for the C&I, $LHV_{C\&I}$. This together with the initial quantity of C&I fuel, $m_{C\&I,initial}$, gives the final quantity of C&I waste that will be used as fuel, $m_{C\&I,final}$. This can be expressed as

$$m_{C\&I,compensation} = \frac{Q_{initial} - Q_{uncompensated}}{LHV_{C\&I}}, \tag{23}$$

$$m_{C\&I,final} = m_{C\&I,initial} + m_{C\&I,compensation}. \tag{24}$$

The added amount of C&I waste will now compensate the difference in initial and after sorting energy quantity. Utilizing eq 15 with $m_{C\&I,final}$ as the quantity for the waste to find the the final energy quantity for the C&I waste, $Q_{C\&I,final}$, the final energy quantity for all streams, Q_{final}, can be found with

$$Q_{final} = Q_{unsorted} + Q_{sorted} + Q_{C\&I,final}. \tag{25}$$

As the energy quantities now have been compensated, the final energy quantity should now be equal to the initial, as in

$$Q_{final} = Q_{initial}. \quad (26)$$

3.4 Emission calculations

This subchapter will discuss how the emissions from the scenarios can be established.

3.4.1 Carbon to CO_2

The conversion of fossil carbon to CO_2 emitted is due to the atomic properties of carbon and oxygen. The atomic weight of carbon is 12 and the atomic weight of oxygen is 16, while the atomic weight of CO_2 is 44. Knowing this ratio, it gives that 1 kg of carbon will combine with 2,67 kg of oxygen to produce 3,67 kg of CO_2 if complete combustion is assumed. Thus, the conversion factor of the share of fossil carbon to CO_2 is 3,67 (Hong & Slatick, 1994).

The mass of the fuel, m_{fuel}, multiplied with the share of fossil carbon for the stream, $\gamma_{C,fossil}$, and the conversion factor will yield the fossil CO_2 emissions from a given stream in tons, $CO_{2fossil}$, as in

$$CO_{2_{fossil}} = m_{fuel} * \gamma_{C,fossil} * 3{,}67. \quad (27)$$

To determine the biogenic emission, $CO_{2biogenic}$, the share of biogenic carbon in the composition, $\gamma_{C,biogenic}$, is used instead of the fossil share, as

$$CO_{2_{biogenic}} = m_{fuel} * \gamma_{C,biogenic} * 3{,}67. \quad (28)$$

For this study, determining biogenic emissions is only important while calculating negative emissions caused by capture technology.

3.4.2 Emissions by streams

Each streams used in a scenario is attributed with the specific parameters discussed in 3.3: the related LHV and share of fossil carbon (and for the cases with CCS the share of biogenic carbon as well) to the constitution of the waste of the stream, and the quantity of the waste for the stream that can be derived from the LHV. The fossil CO_2 emissions for a stream is determined with equation 27. This is sufficient to find the emissions for the cases where the change of emissions derives from a change of the fuel, i.e. sorting or requirement specification. The case for inclusion of CCS technology will be discussed further.

The sum of emissions from all utilized streams i, denoted as CO_{2i}, in a scenario j, then gives the total fossil CO_2 emission for the scenario, CO_{2j}, as

$$CO_{2_j} = \sum CO_{2_i}. \quad (29)$$

To find the relative emission reduction that a scenario contributes with comparative to if no measures are taken, the difference between the emissions for the scenario and the reference case are found. The emissions for the reference case are found with the same method as above. We have

$$\delta CO_{2_j} = CO_{2_{reference}} - CO_{2_j}, \quad (30)$$

where δCO_{2j} is the emission reduction of scenario j compared to the reference case, and $\delta CO_{2reference}$ is the emissions for the reference case.

3.4.3 Determining streams used for requirement specification

The streams used by SE that can be eligible for requirement specification are the Swedish and the imported SRF fuel. These streams are utilized at the P6 facility at Högdalen, where both Swedish and imported SRF are used as fuel, and at the Lövsta plant, where the fuel will be imported SRF exclusively. The emission reduction that can be derived from requirement specification comes from utilizing streams with a smaller share of fossil carbon (i.e. a smaller share of plastics) for fuel, though to which extent the fraction of plastic have to be reduced and for which streams are not given at first. With 9 different requirement specified constitutions produced and the two original constitutions of SRF waste, as shown in figures 4 – 5, and the three different streams where these would be utilized, this yields 150 different combinations of how these streams can be utilized with unique emissions. The difficulty therefore lies in finding which of these combinations that can be used to represent the emission reduction effects that requirement specification can have when comparing to the other studied measures of this study.

To choose which of these combinations to include in the comparison between the different scenarios, the emission reduction resulting from the combination should satisfy the condition that the aggregated emission reduction from the requirement specification and the sorting should be sufficient to offset the added emissions from the Lövsta plant. The condition can be formulated as

$$CO_{2_{Lövsta}} \leq \left\| \delta CO_{2_{sorting}} + \delta CO_{2_{req,Swe,P6}} + \delta CO_{2_{req,Imp,P6}} \right\|, \quad (31)$$

where $\delta CO_{2sorting}$ is the emission reduction gained from sorting, $\delta CO_{2req,Swe,P6}$ and $\delta CO_{2req,Imp,P6}$ is the emission reduction gained from utilization of requirement specified streams at P6 from Swedish and imported waste respectively, and $CO_{2Lövsta}$ is the emissions from Lövsta.

Firstly, to find the emission reduction that one stream has if utilized, we find the difference between that stream and the stream utilized in the reference case. When calculating the emissions from these streams, the energy quantity is consistent, though the mass of the fuel and the carbon share are relative to the LHV and composition of the stream. The emission of a specific stream can be found with eq 27, the difference between the emissions of the streams with eq 30. An overview of the emissions and emission reduction from the different streams can be found in tables 10 – 11. Here it is clear that reducing the amount of plastics in the fuel utilized at Lövsta have the most impact on reducing emissions, due to the size of that stream. Table 12 details the emissions from Lövsta if any of the streams are utilized, which in relation to tables 10 – 11 shows the emission reduction required if an offset of the emissions from Lövsta should be managed.

Table 10: The Swedish SRF fuel and requirement specified Swedish SRF fuel, showing the emissions they would produce when utilized at the P6 furnace at the Högdalen facility and how the emissions of each stream compares to if the original stream was utilized.

Stream	Emissions (kton)	Emission reduction (kton)
Original	45	0
15%	38	-7
10%	28	-17
5%	17	-28
0%	7	-38

Table 11: The imported SRF fuel and requirement specified imported SRF fuel, showing the emissions they would produce when utilized at the P6 furnace at the Högdalen facility and how the emissions of each stream compares to if the original stream was utilized.

Stream	Emissions (kton)	Emission reduction (kton)
Original	18	0
20%	17	-1
15%	13	-4
10%	10	-8
5%	6	-12
0%	3	-15

Table 12: The requirement specified imported SRF fuel, showing the emissions they would produce when utilized at the Lövsta facility. The emission reductions derived from the requirement specification at the Högdalen facility as well as the emission reduction from sorting is then compared to the emissions from Lövsta when the different requirement specified streams are utilized.

Stream	Emissions (kton)
20%	204
15%	164
10%	125
5%	76
0%	32

When the difference for the emissions have been found, for the Swedish and imported SRF at Högdalen, the resulting emission reduction should be combined with the emission reduction found from sorting. It will be the emission reduction effect of a specific combination of the Swedish and imported requirement specified stream *i* for the Högdalen facility, $\delta CO_{2Swe,i}$ and $\delta CO_{2imp,i}$ respectively, together with the emission reduction from the sorting. We will call this combined emission reduction the aggregated emission reduction, $\delta CO_{2aggregated}$. This is expressed in eq 32 as

$$\delta CO_{2_{aggregated}} = \delta CO_{2_{sorting}} + \delta CO_{2_{Swe,i}} + \delta CO_{2_{imp,i}}, \qquad (32)$$

Each individual aggregated emission reduction can then be divided with the CO_2 emission from Lövsta to find the factor, $F_{reduction}$, of how much of the added emissions from Lövsta that the aggregated emission reduction is capable to offset. This should be done for all cases of Lövsta's emissions from the different requirement specified streams. If the factor is more than one, this means that the aggregated emission reduction is sufficient to offset Lövsta, which fulfills the condition. This is expressed as

$$F_{reduction} = \frac{\left\| \delta CO_{2_{aggregated}} \right\|}{CO_{2_{Lövsta}}}. \qquad (33)$$

This yields all combinations of utilization of requirement specification. To represent the scenarios for which requirement specification is relevant, two of the combinations will be chosen to represent the range of the emissions. One combination will be the highest emission that still fulfills the condition to offset Lövsta and the other will be the lowest possible emission from all combinations.

3.4.4 Calculating negative emissions

The total amount of captured CO_2 will be related to the capture rate of the CCS facility and the quantity of the CO_2 released from the fuel. The captured amounts are for the purposes of this study most important for determining the cost of the CCS technology. The captured amounts of CO_2 are calculated in equations 34 to 36 as

$$\delta CO_{2_{CCS,fossil}} = CO_{2_{fossil}} * r_{capture}, \tag{34}$$

$$\delta CO_{2_{CCS,biogenic}} = CO_{2_{biogenic}} * r_{capture}, \tag{35}$$

$$\delta CO_{2_{CCS,tot}} = \delta CO_{2_{CCS,fossil}} + \delta CO_{2_{CCS,biogenic}}, \tag{36}$$

where $r_{capture}$ is the capture rate, and $\delta CO_{2CCS,fossil}$, $\delta CO_{2CCS,biogenic}$ and $\delta CO_{2CCS,tot}$ are the fossil, biogenic and total amounts of captured CO_2 respectively.

The negative emissions produced by the capture of biogenic CO_2 will influence the net emissions from the studied plants. When calculating emissions per stream for the emission per scenario calculations, the net emission after capture should replace the ordinary emission calculation for the stream that is affected by the CCS technology. To estimate the negative emissions CCS technology can provide, both the fossil and the biogenic share of the fuel must be taken into consideration. The steps for determining the fossil or biogenic emissions from a specific stream is presented in chapters 3.4.1-3.4.2. The capture of CO_2 from a fossil source will decrease the net emissions to the extent of the quantity the facility is able to capture. The capture of CO_2 from a biogenic source is regarded differently since biogenic CO_2 does not count towards any fossil emission. All biogenic CO_2 that the facility can capture are regarded to be negative emissions. The negative emissions, $\delta CO_{2negative}$, is then the remaining uncaptured fossil emission minus the captured biogenic emission, calculated as

$$\delta CO_{2_{negative}} = CO_{2_{fossil}} * \left(1 - r_{capture}\right) - CO_{2_{biogenic}} * r_{capture}. \tag{37}$$

3.5 Cost and income calculations

For this subchapter, the different costs and incomes will be detailed in how they are calculated and how they are presented in the comparison between the different scenarios.

3.5.1 Gate fee and tax on combustion of waste

Gate fees are the fees that is paid to a waste to energy actor by the supplier of waste for receiving a quantity of waste (Cho, 2016). Both the income generated by gate fees for the received waste and the cost of the tax on incinerated waste are relative to the quantities of waste that SE handles, therefore they have been combined for the calculations to give a combined net income related to the quantities of waste as

$$I_{GF,net} = \sum(I_{GF,i} - C_{tax,i}), \tag{38}$$

$$I_{GF,i} = m_{GF,i} * P_{GF}, \tag{39}$$

where $I_{GF,net}$ is the net income from received gate fees for a scenario after the tax costs have been considered, $I_{GF,i}$, $m_{GF,i}$ and $C_{tax,i}$ is the income from gate fees, the gate fee generating quantity of waste and tax cost for a stream i, and P_{GF} is the price of the gate fee. The price for the gate fees were taken from an investigation of the waste to energy market made by the independent consulting firm Profu, where the prognosis for the price for gate fees in 2024 in southeastern Sweden is a low case of 350 SEK/ton, a median case of 460 SEK/ton, and a high case of 550 SEK/ton (Profu, 2019, p 35).

As the income from gate fees rely on the quantities of waste that is received to the facility, the gate fee generating quantity will for most cases be the same as the quantity for the fuel that will be incinerated. Some of the streams that are sorted are an exception to this. For the case of sorting in HSMA at Högdalen, the cost for the sorting facility is paid by Stockholm Vatten. It is therefore assumed that the only waste that would reach the facility of SE is the sorted waste and that therefore SE would gain no gate fee that have been sorted out in HSMA. For the case of the sorting in BOSS at the Brista facility, the opposite is assumed. Here it is assumed that SE pays the full cost for the sorting facility and that they also would gain income from gate fees on the waste that have been separated from the fuel, as it would have been received by SE. The gate fee generating quantity would therefore be the quantity of the fuel and the quantity of the waste that have been sorted out, as detailed by equation 21. The gate fee generating quantity for BOSS, $m_{GF,BOSS}$, is then

$$m_{GF,BOSS} = m_{fuel} + m_{separated}. \tag{40}$$

In the case of the extended sorting facility at Högdalen, we assume that SE would pay the full cost for the extension. As the extended facility is designed to be of an equal capacity to the original, and that Stockholm Vatten still would pay for the original facility, we assume that the gate fee generating stream would add half of the sorted out waste, i.e. the waste sorted out by the extended facility. The gate fee generating quantity for the extended sorting at HSMA, $m_{GF,HSMA,extended}$, can be expressed as

$$m_{GF,HSMA,extended} = m_{fuel} + 0{,}5 * m_{separated}. \tag{41}$$

The cost of the tax on waste incineration is relative to the quantity of waste that is received to the facility and used for fuel. This creates another necessity to clarify which quantity of waste that is under scrutiny for taxation. In contrast to the gate fee generating quantities, the only quantity that must be considered in this case is the quantity actually used as fuel. Thus, in all cases the quantity of the fuel is the same as the quantity of the taxable waste. We have

$$C_{tax,i} = m_{tax,i} * P_{tax}, \tag{42}$$

$$m_{tax,i} = m_{fuel}, \quad (43)$$

where $m_{tax,i}$ is the taxable quantity for stream i, and P_{tax} is the price for the tax in SEK/ton. The recently introduced tax is of 2022 and afterwards at 125 SEK/ton of waste (Sveriges Riskdag, 2019, p 5).

3.5.2 Cost and income for CCS

As described in 2.5.1, the cost for CCS relies on the quantity of CO_2 that is captured and transported and stored. The captured CO_2 is the total amount of both fossil and biogenic, as of equation 36. The net cost of CCS for the facilities will also rely on whether the practice could be eligible to receive investment incentives, in the form of reverse auctioning or however else it could manifest. It is assumed only the biogenic share of the captured CO_2 would be eligible for incentives, therefore the share of biogenic CO_2 from the stream that utilizes CCS should be multiplied to the cost of CCS to find the income gained from incentives. In the results, two cases will represent when incentives are counted for and when not, to highlight the dependency of incentives that could arise. This is expressed in the equations as

$$C_{CCS,tot} = \delta CO_{2_{CCS}} * \left(C_{CCS,capture} + C_{CCS,T\&S}\right), \quad (44)$$

$$I_{CCS,subvention} = \gamma_{CO_2,bio} * C_{CCS,tot}, \quad (45)$$

$$C_{CCS,net} = C_{CCS,tot} - I_{CCS.incentive}, \quad (46)$$

where $C_{CCS,tot}$, $C_{CCS,net}$, $C_{CCS,capture}$ and $C_{CCS,T\&S}$ are the the total cost for CCS, net cost for CCS, cost for capture and cost for transport and storage respectively. $I_{CCS,incentive}$ is the income derived from incentives for negative emissions, and $\gamma_{CO_2,bio}$ is the share of biogenic emissions derived from the fuel.

As the cost and potential for the implementation of CCS on KVV-8 (scenario 3.1) is taken from a Lehvin et al. (2019), where the cost for capture was calculated as 37 €/ton CO_2, with conversion to SEK as of 392 SEK/ton. This study also gives the data for the transport and storage costs as 23-42 €/ton, conversed into between 244-530 SEK/ton with 387 SEK/ton for the median cost case. The capture cost for Lövsta was gathered from more general estimations of capture costs for CCS, which was set with conversion to 1059 SEK/ton (Klimatpolitiska vägvalsutredningen, 2020).

3.5.3 Cost of EUA by scenario

SE, as a producer of energy with waste incineration, are subject of the European Union Emission Trading System (EU-ETS) (Naturvårdsverket, 2020b). This requires the company to trade for European Union Allowances (EUA) relative to their fossil emissions, where each acquired EUA gives the company the right of emitting 1 ton of CO_2 equivalents (Naturvårdsverket, 2020c).

The cost of trading for the EUA for each stream depends on the fossil emissions emitted by that stream i, the amount of allocated free allowances, $CO_{2,free,i}$, and the price for EUA, P_{EUA}. The total cost of each stream can then be summarized to give the cost for EUA for the scenario as

$$C_{EUA} = \sum(CO_{2_{fossil,i}} - CO_{2_{free,i}}) * P_{EUA}. \quad (47)$$

The price for EUA for this study was estimated with the aid of an employee of SE to 266 SEK/ton (Sandberg, 2020). The quantity of free allocations for a stream are determined from the energy quantity of that stream and a factor for free allocations per produced energy, F_{free}, gathered from a previous example on the free allocations on the Högdalen plant where it was found to be between 42-53 EUA/GWh produced energy with 47,5 EUA/GWh as a median (Dotzhauer, 2020). The free allowances for a stream can be calculated as

$$CO_{2_{free,i}} = Q_i * F_{free}. \quad (48)$$

3.5.4 Cost of sorting

The cost of sorting for the scenario, $C_{sorting}$, is calculated by attributing the cost for a sorting facility, as detailed in 2.3.1, to the stream that is sorted and summarize all costs, as in

$$C_{sorting} = \sum C_{sorting,i}, \quad (49)$$

where $C_{sorting,i}$ is the cost for sorting stream i. As mentioned above in 3.5.1, the sorting facility HSMA is paid for by SVOA and is assumed not to result in any costs for SE. Futhter assumptions is that SE covers the full costs for BOSS, as this study have no insight in the agreement between the joint owners of the facility SE and SÖRAB. The annual cost for BOSS is estimated to 20,4 mSEK, from the operational costs of 18,4 mSEK, the remaining capital cost after inclusion of the investment support of 246 mSEK distributed over a operational period of 20 years, and the estimated income from recovered materials of 10,3 mSEK, that is assumed to be applicable to BOSS as well as HSMA. The extended sorting at Högdalen is assumed to have the same cost as BOSS.

3.5.5 Absolute cost for the scenarios

To show the absolute cost for each scenario, the reference case included, all above described costs and incomes are summarized. This represent the actual cost for the scenario, without regard to how efficient it is in reducing emissions. We have

$$C_{j,abs} = C_{EUA} + C_{sorting} + C_{CCS,net} - I_{GF,net}, \quad (50)$$

where $C_{j,abs}$ is the absolute cost for scenario j.

3.5.6 Relative cost of emission reduction

For a measurement that better reflect the cost efficiency of the scenarios ability to reduce fossil emissions, we find the relative cost for the scenario in relation to the emission reduction of the scenarios. This can be calculated as

$$C_{emission\ reduction,j} = \frac{C_j}{\delta CO_{2_j}}, \tag{51}$$

where $C_{emission\ reduction,j}$ is the relative cost of emission reduction for scenario j, and C_j is the cost for scenario j. The cost for the scenario is relative to the reference case, i.e. if no measures are taken to reduce the emissions. Here the costs of the scenario include the cost for CCS and sorting, as they are added costs that are not included in the reference case. The emission reduction for the scenarios can be found with equation 30. We have

$$C_j = C_{CCS,net} + C_{sorting}, \tag{52}$$

3.5.7 Relative income to the reference case

The change of the quantity of waste needed as the LHV is lowered by sorting or requirement specification and the decrease of emissions will have an impact on the incomes for the scenarios. The incomes relative the reference case show how much income is generated through the measures taken and shows to what degree the measures can pay for themselves. This is calculated as

$$\delta I_j = \delta I_{GF,net} + \delta I_{EUA}, \tag{53}$$

$$\delta I_{GF,net} = I_{GF,net,j} - I_{GF,net,reference}, \tag{54}$$

$$\delta I_{EUA} = C_{EUA,reference} - C_{EUA,j}, \tag{55}$$

where δI_j, $\delta I_{GF,net}$, and δI_{EUA} are the change of income for the scenario j, the net gate fees and EUA, $I_{GF,net,j}$ and $I_{GF,net,reference}$ are the net incomes from gate fees for scenario j and the reference case, and $C_{EUA,reference}$ and $C_{EUA,j}$ are the costs for EUA for the reference case and scenario j. Here the cost for EUA credits is counted as an income, since relative to the reference case where no measures to reduce emissions are taken the scenarios have a lower cost for EUA. The income from EUA then represent the reduced demand to pay for emission credits.

4. Results

The results of the calculations described previously is presented in this chapter.

4.1 Properties of the streams

Here the properties of the streams of waste necessary to calculate both emissions and costs for a scenario will be displayed. The necessary properties include the individual compositions and heating values for a stream as well as the different quantities of a stream.

4.1.1 Determine composition for streams

By using the original streams for MSW, imported SRF and Swedish SRF as a template, the sorted and requirement specified streams could be determined by implementing the methods detailed in 3.2.7. Further, the moisture content for each stream can be determined with the methods detailed in 3.2.6. The composition for the streams in dry is detailed in figures 4 – 6, while the compositions in ar is presented in the appendix.

The imported SRF streams have a large share of wood that have a relatively high heating value and a low moisture content, keeping the heating value high even with lower contents of plastics. Paper also have a considerable share, having a similar effect on the LHV of the compositions while assumed to hold more moisture than wood, therefore slightly raising the total moisture content of the streams. It should be noted that textile is one of the fractions that have been lowered to comply with the fuel specification of Lövsta. It is a reasonable simplification to apply the same limitation of textile to all imported SRF streams.

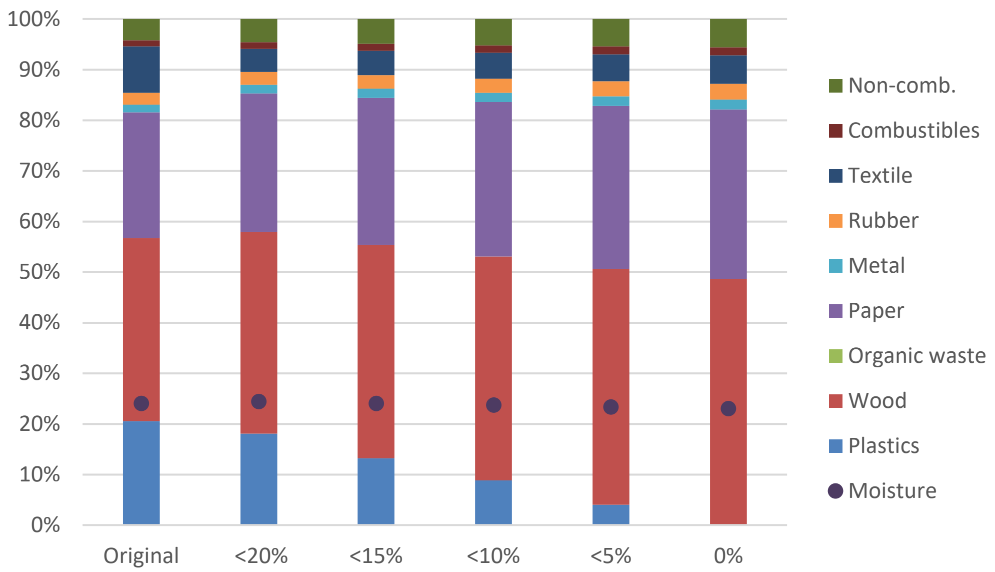

Figure 4: Shares of fractions (in %) for the imported SRF waste streams in dry, ordered by the allowed quantity of plastics in the stream. Original composition of SRF imported waste gathered from personal communicaitions with Lindman (2019).

Similar conditions as for the imported SRF apply to the Swedish SRF. Here the share of wood is slightly larger and the share of paper slightly smaller. No manipulation of the share of textile have been done for any of the Swedish SRF streams.

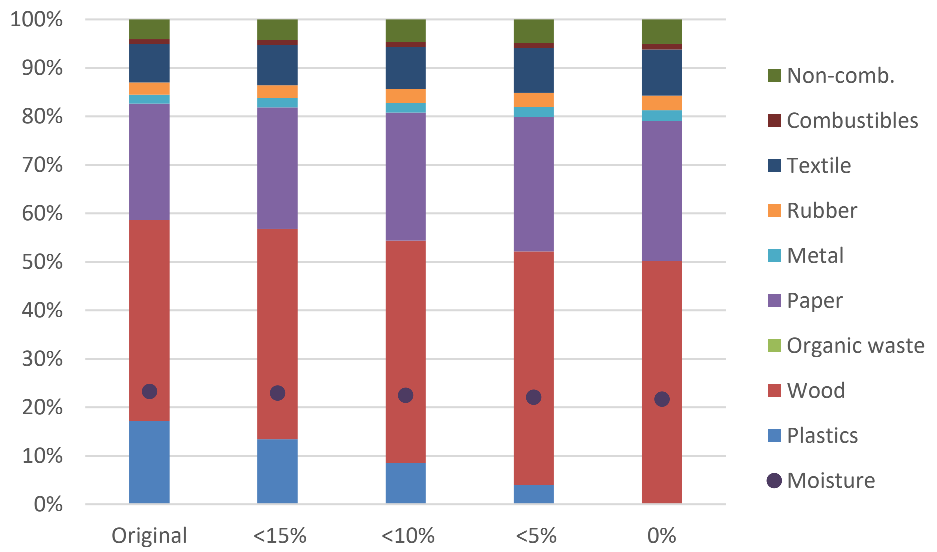

Figure 5: Swedish SRF waste in dry. Original composition for Swedish SRF waste gathered from personal communication with Lindman (2019).

To represent the sorted MSW streams the individual sorting rates of the two sorted stream have been applied. The MSW-fuel sorted at the HSMA facility or the for this study proposed identical facility at Högdalen have sorting rates at 75% of the plastics, 40% of the organic material and 90% of the metal. This yields a composition where unspecified combustibles have a high share of 36,2% of the weight, for this study assumed to only have 3% fossil coal of dry material, but in reality it could be hard to give an exact estimation. Paper have a large share as well and the plastics constitutes 6% of the dry weight. For the waste sorted at the BOSS facility at Brista, the sorting rates are 75% of plastics, 25% of organic material and 90% of metal. Expectedly the larger share of organic material in this stream allows for a higher moisture content, while the fossil materials are slightly lower in this case.

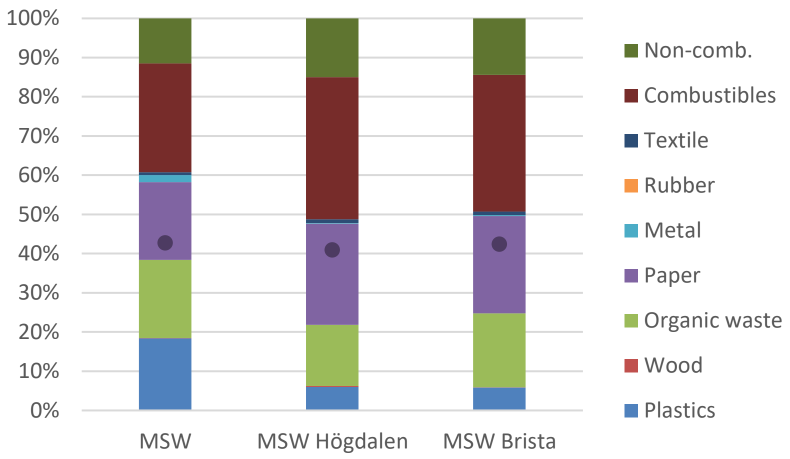

Figure 6: MSW streams in dry

4.1.2 Lower heating value for streams

Completing the calculations for determining the LHV for each stream, using the method explained in 3.3.1, it is apparent that the values for the industrial waste is higher than expected. In similar calculations, utilizing a finer analysis on the imported industrial waste, the LHV could be found to be closer to 3,9 MWh/ton. The difference in the result does not come down to calculation error, but rather to the difference in precision to give a good projection of the elemental composition of a stream by different methods. The comparable method utilized laboratory made flue gas analysis of the SRF waste, while the method used here is a mathematical model that relies on general data for the elemental compositions of the fractions of waste. For the households waste however, comparable calculations only had access to the data used for this study and that result yielded the same result as here. For comparability between the calculations for the different stream for this study, the same method for determining the lower heating value have been used for all streams. The corresponding LHV for each stream is detailed in figure 7.

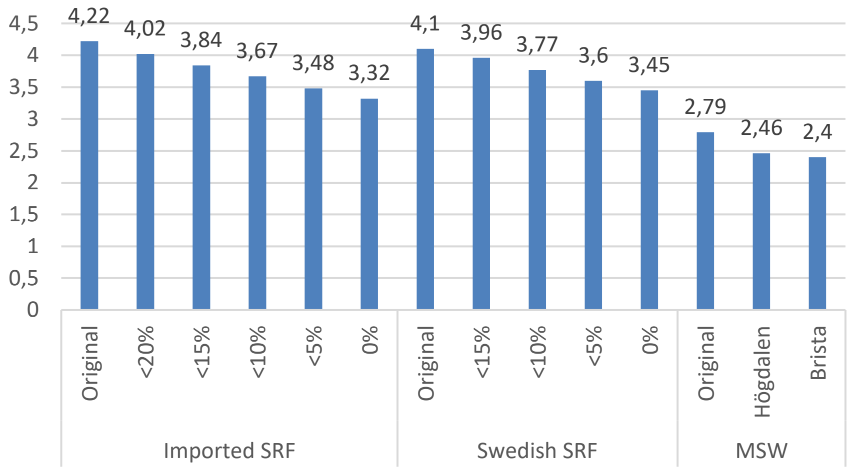

Figure 7: Corresponding heating value for each stream of waste, grouped by type of waste.

4.1.3 Share of carbon of streams

Closely related to finding the individual LHV for each stream, as calculating LHV relies on the elemental shares of the stream, is finding the share of fossil and biogenic carbon each stream has. The shares of fossil and biogenic carbon in ar for each stream are presented in table 13 below.

Table 13: Corresponding shares (%) of fossil and biogenic carbon of each stream in ar.

	Stream	Fossil	Biogenic
Imported SRF	Original	12,4	24,4
	<20%	11,1	24,4
	<15%	8,5	26,0
	<10%	6,2	27,4
	<5%	3,6	29,0
	0%	1,4	30,3
Swedish SRF	Original	10,7	25,5
	<15%	8,7	26,7
	<10%	6,1	28,4
	<5%	3,6	30,0
	0%	1,4	31,4
MSW	Original	8,2	17,8
	Högdalen	3,2	21,0
	Brista	3,0	20,8

4.1.4 Quantities of streams

It is necessary to know the quantities of waste that is treated, both to determine fossil emissions and costs and income for SE. The quantity for a specific stream is determined by using the methods detailed in chapter 3.3.6. The distinction between the taxable and gate fee generating quantities, as of the method presented in 3.5.1, is also highlighted here for clarity on the quantities related to the economic calculations of this study.

For scenario 1.1, the capacity for the sorting facilities were set to 134 kton, and the initial incoming streams of MSW was estimated with equation 15 to approximately 440 kton for Högdalen and 76 kton for Brista. This means a portion of the waste in Högdalen will be redistributed to fill the capacity for BOSS, the quantity of the redistributed waste found with equation 17. To determine the quantity of the sorted waste left after sorting, thus the quantity that will be used as fuel, the factor for the remaining waste is considered. The factor for HSMA is slightly lower than the factor for BOSS, due to that HSMA is designed to redistribute ca 17 600 tonnes organic material while BOSS is designed for 10 000 tonnes for this model. The factor is given by equation 9.

The change of energy content for the available fuel is compensated by the C&I waste stream. For Högdalen, approximately 104 kton extra industrial waste is needed to maintain the designed input energy. Since Brista in this scenario received household waste from Högdalen to utilize the sorting capacity to its full extent, the quantity of industrial waste is approximately 10 kton less than the case without sorting. The final quantity of the streams used as fuel in Högdalen and Brista is as in table 14 below.

Table 14: kton of initial, final and sorted quantities for the streams of waste used at Högdalen and Brista for the scenario with the planned sorting capacity, as well as a highlighting of the taxable quantities and the quantities that generate a gate fee.

Site	Stream	Initial quantities of waste	Final quantity of fuel	Quantity of sorted from stream	Taxable quantity	Gate fee generating quantity
P1-P4	MSW	441	249	0	249	249
	MSW Högdalen	0	100	35	100	100
	C&I	110	215	0	215	215
B2	MSW	76	0	0	0	0
	MSW Brista	0	106	28	106	134
	MSW imp	33	33	0	33	33
	C&I	102	88	0	88	88

The same methods as were used for scenario 1.1 are used to calculate the quantities of waste that can be used as fuel for scenario 1.2. As evident from the lack of incoming household waste to the Brista site to fully utilize the sorting capacity, only the sorting capacity for Högdalen will be extended. The extension should be imagined as a second facility of an equal size as HSMA, thus the sorting capacity for this scenario is 268,4 kton/year for two sorting facilities at Högdalen and remaining at 134 kton for BOSS at Brista. The scenario is not extended further due to that the incoming quantity of waste to Högdalen would not cover the capacity for three facilities at Högdalen and the redistributed quantity for BOSS.

For this scenario, the final quantities for Brista are unchanged from the previous scenario. For Högdalen, the quantity of sorted fuel is expectedly doubled and there is a greater dependence on compensation with C&I waste. The quantities are detailed in table 15.

Table 15: kton of initial, final and sorted quantities for the streams of waste used at Högdalen and Brista for the scenario with extended sorting capacity, as well as a highlighting of the taxable quantities and the quantities that generate a gate fee.

Site	Stream	Initial quantities of waste	Final quantity of fuel	Quantity of sorted from stream	Taxable quantity	Gate fee generating quantity
P1-P4	MSW	441	115	0	115	115
	MSW Högdalen	0	199	69	199	234
	C&I	110	261	0	261	261
B2	MSW	76	0	0	0	0
	MSW Brista	0	106	28	106	134
	MSW imp	33	33	0	33	33
	C&I	102	88	0	88	88

For the streams not affected by sorting the quantity is easier to establish by dividing the set energy quantity for the stream with the calculated LHV for the stream as in equation 15. As all fuel of these streams that are received by SE are assumed to be used as fuel, the taxable and gate fee generating quantities are the same.

4.2 Emission reductions compared to emissions from Lövsta

Here we find whether the emission reductions from requirement specification and sorting combined can be able to offset the emissions from the proposed Lövsta facility, the method described in chapter 3.4.3. The aggregated emission reduction is compared to the emission from Lövsta, when Lövsta utilizes the different variations of the imported SRF-fuel detailed in figures 4 and 5. The aggregated emission reduction divided by the emission from Lövsta yields a percentage of how great the emission reduction is compared to Lövsta, if the result is over 100% the measures are enough to off-set Lövsta completely.

4.2.1 Emission reduction from sorting compared to Lövsta

For scenario 1.1 concerning when only the sorting facilities currently planned for are available, the total emission reduction compared to the reference case are approximately 30 kt CO2. For the extended sorting in scenario 1.2, the emission reduction amounts to about 44 kton CO2. The calculated emissions from Lövsta are about 204 kton CO2 for both scenarios since the waste stream used at Lövsta is not included among the sorted streams. The sorting facilities included in scenario 1.1 and 1.2 only manages to off-set approximately 15% and 22% respectively of the added emissions from Lövsta, thus both scenarios fail to fulfill that condition independently. As sorting is included in all scenarios however, the emission reduction effects of sorting carries over to the other scenarios aggregated emission reduction.

4.2.2 Emission reduction from requirement specification and already planned for sorting compared to Lövsta

For scenario 2.1, when the emission reduction of the sorting of the MSW waste, as of scenario 1.1, and the requirement specification on the SRF fuel used at the Högdalen site are compared to the emissions from Lövsta, it is clear that the aggregated emission reduction have a great difficulty in off-setting the emissions derived from the Lövsta plant. As shown in table 16, when the combined measures compare to Lövsta's emissions when the fuel used at Lövsta are of the SRF streams with 10% plastics or more, no combination of requirement specification of the imported and Swedish SRF-fuel used at Högdalen and the sorted fuels yields an emission reduction great enough to off-set Lövsta. Not until the measures are compared to the emissions from Lövsta with the stream of 5% maximum plastics can a combination where the aggregated emission reduction is greater than the emission from Lövsta. Only if the Swedish SRF contain no amount of plastics and the imported SRF contain a maximum of 5% of plastics can the comparison yield a result greater than 100%.

Table 16: The percentage of the aggregated emission reduction from planned sorting and requirement specification on the fuel for the Högdalen site to the emissions from Lövsta with a maximum of 5% plastics in the fuel.

		Imported SRF					
		Original	<20%	<15%	<10%	<5%	0%
Swedish SRF	Original	39,6	41,0	45,3	49,5	54,7	59,5
	<15%	48,9	50,3	54,6	58,8	64,1	68,8
	<10%	62,4	63,8	68,1	72,4	77,6	82,4
	<5%	76,3	77,7	82,0	86,3	91,5	96,3
	0%	89,8	91,2	95,5	99,7	105,0	109,7

Comparing the emission reductions to Lövsta when no plastics are allowed in the fuel highlights the importance of reducing the emissions from Lövsta for the plausibility to offset the emissions from the facility. When no plastics are allowed for the SRF-fuel for Lövsta, almost all combinations of emission reduction are sufficient to yield a result of over 100%. As seen in table 17, only when the Swedish SRF-fuel have no specification on the allowed percentage of plastics and when the imported SRF-fuel have a maximum of 20% plastics or are unchanged from the original constitution are the aggregated emission reduction not great enough to off-set Lövsta.

Table 17: The percentage of the aggregated emission reduction from planned sorting and requirement specification on the fuel for the Högdalen site to the emissions from Lövsta with 0% plastics in the fuel.

		Imported SRF					
		Original	<20%	<15%	<10%	<5%	0%
Swedish SRF	Original	95,3	98,8	109,1	119,3	131,9	143,5
	<15%	117,7	121,2	131,6	141,8	154,4	165,9
	<10%	150,3	153,8	164,2	174,4	187,0	198,5
	<5%	183,9	187,3	197,7	207,9	220,5	232,0
	0%	216,3	219,8	230,1	240,3	252,9	264,4

4.2.3 Emission reduction from requirement specification with extended sorting compared to Lövsta

When considering an extended sorting for scenario 2.2 the aggregated emission reduction expectedly becomes greater, but not to an extent where the Lövsta emissions are remarkably easier to off-set with requirement specifications. As with scenario 2.1, no comparison yields a value greater than 100% when more than 5% plastics are allowed in the SRF-fuel for Lövsta, detailed in table 18. In the case where the maximum allowed share of plastics in the Lövsta fuel are set to 5%, slightly more comparisons yield over 100% than in the same comparison for the previous scenario. Here it is sufficient with a maximum of 15% plastics in the imported SRF, if the Swedish SRF are kept to a maximum of 5%. The case when the Swedish SRF contains no more than 10% plastics can also off-set the Lövsta emissions, but for that the imported SRF cannot contain any plastics.

Table 18: The percentage of the aggregated emission reduction from extended sorting and requirement specification on the fuel for the Högdalen site to the emissions from Lövsta with a maximum of 5% plastics in the fuel.

		Imported SRF					
		Original	<20%	<15%	<10%	<5%	0%
Swedish SRF	Original	58,7	60,1	64,4	68,6	73,9	78,6
	<15%	68,0	69,4	73,7	77,9	83,2	87,9
	<10%	81,5	82,9	87,2	91,5	96,7	101,5
	<5%	95,4	96,8	101,1	105,4	110,6	115,4
	0%	108,9	110,3	114,6	118,8	124,1	128,8

When the SRF-fuel used for Lövsta is required to contain 0% plastics, all comparisons yield a value over 100%, which can be seen in table 19. In this case, the extended sorting would be sufficient to off-set the emissions from Lövsta, regardless of any requirement specifications for the fuel used at the Högdalen facility.

Table 19: The percentage of the aggregated emission reduction from extended sorting and requirement specification on the fuel for the Högdalen site to the emissions from Lövsta with 0% plastics in the fuel.

		Imported SRF					
		Original	<20%	<15%	<10%	<5%	0%
Swedish SRF	Original	141,4	144,8	155,2	165,4	178,0	189,5
	<15%	163,8	167,3	177,6	187,8	200,4	211,9
	<10%	196,4	199,9	210,2	220,4	233,0	244,5
	<5%	229,9	233,4	243,7	254,0	266,5	278,1
	0%	262,4	265,8	276,2	286,4	299,0	310,5

Since the quantities of waste, heating values and resulting fossil emissions are individual to a specific combination of requirement specified streams, scenarios 2.1 and 2.2 will further in the study be represented by a high emission and a low emission case, where the high emission case will be the combination of streams that allows for the most lenient requirement specification to fulfill the condition to off-set the emissions from Lövsta. For 2.1 this is the combination of the Swedish SRF with 0% plastics, imported SRF with <5% plastics and <5% plastics in the Lövsta SRF. For 2.2 it is when Swedish SRF contain <5% plastics, imported SRF <15% plastics and the Lövsta SRF <5% plastics. The low emission cases are when all streams contain 0% plastics for both scenarios. The study will refer to these distinctions as 2.1 (high), 2.1 (low), 2.2 (high) and 2.2 (low).

4.2.4 Emission reduction from CCS compared to Lövsta

For the scenarios considering implementation of CCS technology one one of SE’s plants, KVV-8 for scenario 3.1 and Lövsta for scenario 3.2, comparing the scenarios emission reduction to the emissions from Lövsta is as straightforward as for the case with sorting facilities. Both scenarios readily fulfill the condition to off-set the emissions from Lövsta, as the capture of biogenic CO_2 produces negative emissions. For scenario 3.1, the negative emissions from KVV-8 are 850 kton, an negative emission about 417% greater than Lövsta’s emissions of 204 kton. With the added emission reduction from sorting the emission reduction for scenario 3.1 reaches about 880 kton.

For scenario 3.2, as Lövsta itself is a producer of negative emissions, the offset of Lövsta’s emissions are self-evident. The biogenic share of the fuel produces 404 kton negative emissions. As the capture rate of the CCS-facility is set to 90%, Lövsta still emits 20,4 kton of the 10% of the fossil CO_2 that the facility is unable to capture, giving a net total of the negative emissions from Lövsta of 383 kton. The total emission reduction for scenario 3.2, including the reduction form sorting, amounts to 617 kton.

4.3 Emissions per scenario

In this chapter, the total emissions per scenario discussed previously will be further compared with each other and detail how they relate to the reference case.

Comparing the total fossil emissions per scenario (figure 8) to each other shows the range of possible emission reduction the measures included in the scenario can have. The scenarios only including sorting is only a relatively small improvement to the reference case, 468 kton CO2 for scenario 1.1 and 453 kton for 1.2, compared to the 498 kton fossil emissions of the reference case. A sharper improvement can be found for the requirement specification scenarios, scenario 2.1 ranging between 240 – 288 kton CO2 for the lowest and highest included emissions, and similarly between 225 – 291 kton for scenario 2.2, about half of the emissions in the reference case. Notably here is that of these emissions 2.2 (high) have the highest emissions even with inclusion of extended sorting in the scenario. This stems from that the extended sorting allows for a higher share of plastic in the imported SRF, leading to a greater emission that still can off-set the emission from Lövsta.

Looking at the scenarios involving CCS, over all negative emissions are reached for the studied plants. The net sum of the emissions for scenario 3.1 leaves 383 kton of negative emissions. Scenario 3.2 also have a net emission under 0, with 119 kton negative emissions.

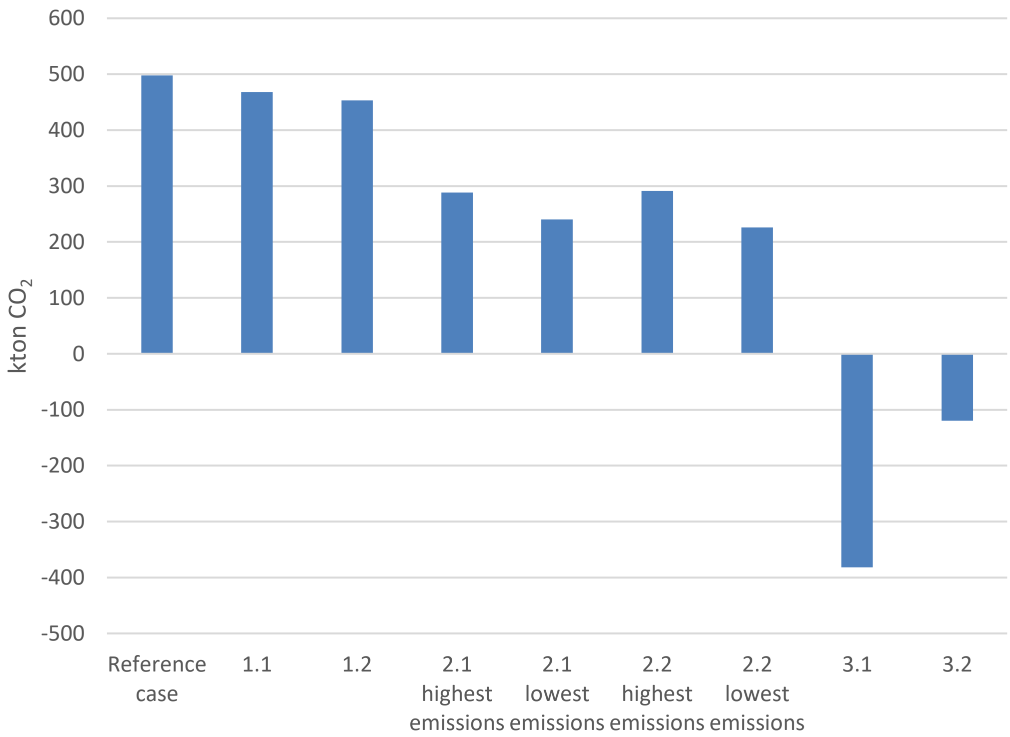

Figure 8: Net annual fossil CO_2 emission for each scenario in kton, including the reference case.

The net decrease of fossil emissions compared to the reference case, presented in figure 9, show the difference between the scenarios and the reference case. The set decrease of 1.1 and 1.2 are the smallest of the comparison, 30 and 44 kton respectively. The net decrease for 2.1 (high) is 209 kton and for 2.1 (low) 258 kton. Scenario 2.2 show a net decrease of 206 kton for 2.2 (high) and 27,2 kton for 2.2 (low). The largest difference is found for scenario 3.1 with a decrease of 880 kton while the second largest decrease are for 3.2 with 617 kton.

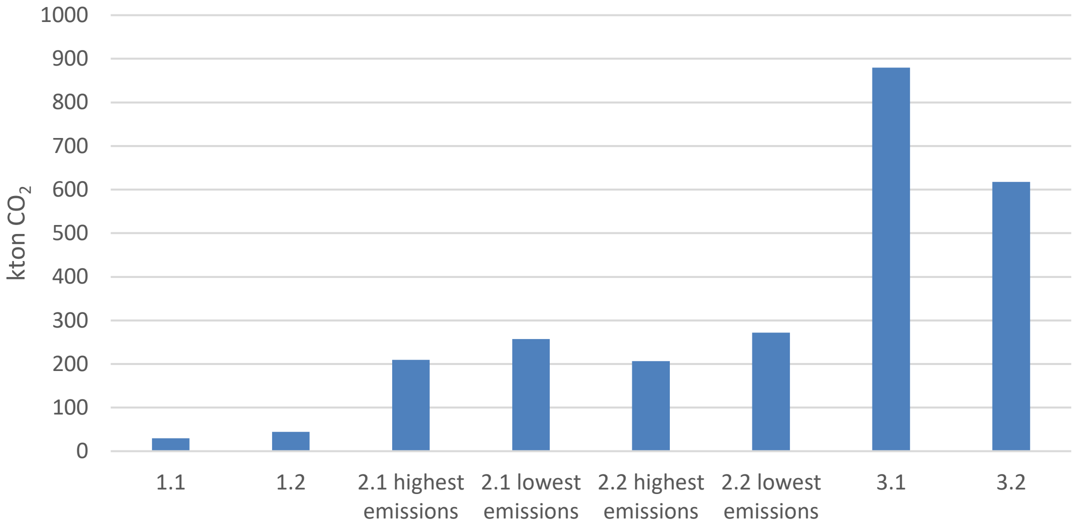

Figure 9: Net decrease of annual fossil CO_2 emissions in kton for each studied scenario compared to the reference case.

4.4 Costs

Table 20 shows the incomes and costs related to each scenario, expressed in mSEK. Each scenario is represented by a low, median and high cost case, where for example the high case is comprised of the highest costs and the lowest incomes related to the scenario.

The calculations show that the net income from received gate fees are large enough to cover for any expenses related to the emission reduction measures in most cases. The reduced CO_2 emissions also result in lower costs for EUA relative to the reference case where no emission reduction measures have been applied. The relative income for each scenario will be detailed further in this chapter.

For scenarios 1.1 and 1.2, with planned for respectively extended sorting, the calculations show a net increase of the profitability relative to the reference case even after including the costs for the sorting facilities. As for all scenarios, the net income increase comes from an increase in admitted quantities of waste generating gate fee income, and a reduced cost for EUA. As the sorting facility HSMA at Högdalen is fully paid for by SVOA, all extra income related to the extra waste and reduced emission caused by that specific facility comes with no added cost for SE. The overall income increase and reduction of EUA costs are great enough to cover for the costs from the other studied sorting facilities according to these calculations.

The scenarios related to requirement specification, scenarios 2.1 and 2.2, show a net increase of income relative to the reference case. This is expected as requirement specification of the fuel does not carry a cost by itself, as it is assumed for this study that any sort of cost for fulfilling the specified requirements of the fuel would be carried by the delivering partner. The received quantities of the fuel increase sharply as the LHV of the fuel is lowered by the stricter requirement specification, resulting in a significant income from the gate fee from the extra waste. It could impact the level of the gate fee that SE would be able to negotiate for such an arrangement though, thus it is of interest that even the high cost cases where gate fees are set to 350 SEK/ton still results in a net income for SE.

The cases where overall profitability cannot be proven under all circumstances are the scenarios where CCS have been implemented. The technology is too costly for the income related to quantities or reduced emissions from waste to cover and relies on incentives to be profitable. The scenario with incentives for CCS on KVV-8 shows the same level of increased profitability as scenario 1.1, as the costs for CCS are assumed to be completely covered by incentives and it otherwise have the same characteristics as scenario 1.1. When no incentives are counted for it becomes unprofitable, except for the low cost case where it barely succeeds with a net profitability of 13,3 mSEK yearly. For scenario 3.2 with CCS at Lövsta it is considerably harder to reach profitability even with incentives, as the incentives only covers the biogenic share of the CO_2 that is captured and with a capturing cost that is larger than for KVV-8. Regardless of the decrease of the cost for EUA, which is great due to the captured share of the fossil emissions at Lövsta, it is not nearly enough.

Table 20: Incomes, costs and net costs for the low, median, and high income for each studied scenario. Incomes and costs are given in mSEK.

	Cost case	GF-Tax	EUA	CCS	Sorting	Net costs
Ref. case	Low	603,8	65,1	-	-	- 538,7
	Median	475,9	72,1	-	-	- 403,8
	High	319,6	79,1	-	-	- 240,6
1.1	Low	630,8	57,1	-	20,4	- 553,3
	Median	498,0	64,1	-	20,4	- 413,5
	High	335,6	71,1	-	20,4	- 244,1
1.2	Low	654,9	53,3	-	40,8	- 560,8
	Median	517,9	60,2	-	40,8	- 416,8
	High	350,4	67,2	-	40,8	- 242,4
2.1 highest emissions	Low	675,4	9,4	-	20,4	- 645,6
	Median	533,1	16,4	-	20,4	- 496,3
	High	359,2	23,4	-	20,4	- 315,4
2.1 lowest emission	Low	687,9	- 3,4	-	20,4	- 671,0
	Median	543,0	3,6	-	20,4	- 519,1
	High	365,9	10,5	-	20,4	- 334,9
2.2 highest emissions	Low	695,1	10,1	-	40,8	- 644,1
	Median	549,5	17,1	-	40,8	- 491,6
	High	371,7	24,1	-	40,8	- 306,7
2.2 lowest emissions	Low	712,0	- 7,3	-	40,8	- 678,5
	Median	562,9	- 0,3	-	40,8	- 522,4
	High	380,6	6,7	-	40,8	- 333,2
3.1	Low	630,8	57,1	-	20,4	- 553,3
	Median	498,0	64,1	-	20,4	- 413,5
	High	335,6	71,1	-	20,4	- 244,1
3.1 no sub.	Low	630,8	57,1	540,0	20,4	- 13,3
	Median	498,0	64,1	661,6	20,4	248,1
	High	335,6	71,1	783,1	20,4	538,9
3.2	Low	630,8	8,2	239,4	20,4	- 362,8
	Median	498,0	15,2	265,7	20,4	- 196,7
	High	335,6	22,2	292,0	20,4	- 1,1
3.2 no sub.	Low	630,8	8,2	765,1	20,4	162,9
	Median	498,0	15,2	849,1	20,4	386,7
	High	335,6	22,2	933,0	20,4	640,0

To evaluate the cost effectiveness for the measures included in the scenarios relative to the emission reduction they allow for, we divide the cost of the scenario with the relative emission reduction compared to the reference case (figure 10). Included in the cost are the costs for sorting and CCS. The relative emission reduction is the difference between the scenario's emission and the emission of the reference case, as shown in figure 9. The cost is given in SEK/ton CO_2 reduced. It should be noted that only CCS have cost variation included in the model in that the cost is a range rather than a fixed number, thus the relative cost for the CCS scenarios are the only ones to be displayed in the different cost cases as in table 20 above.

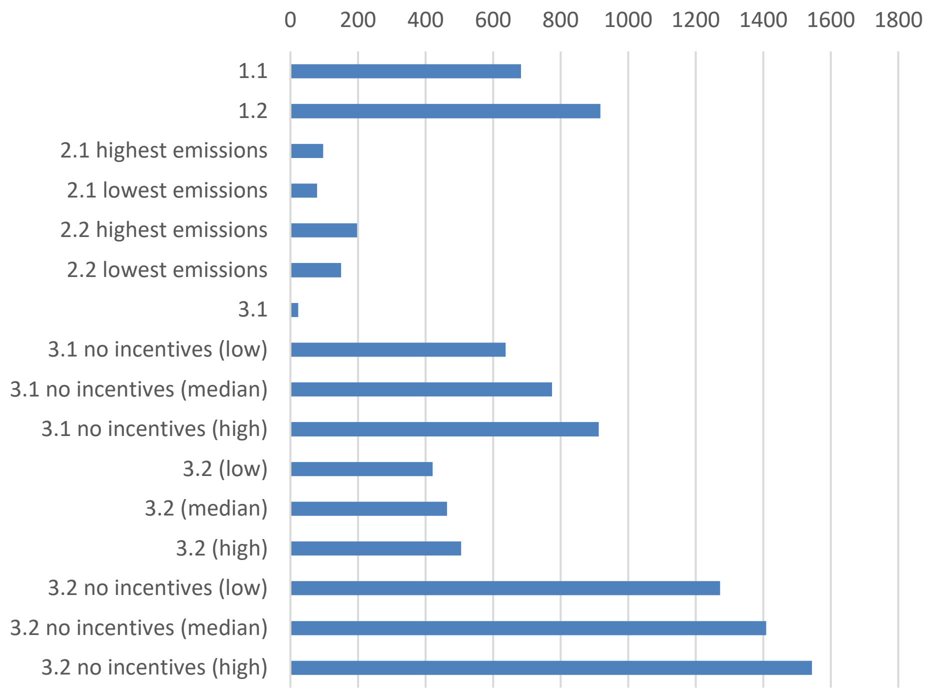

Figure 10: Relative cost per fossil emission reduction in SEK/ton for each scenario compared to the reference case.

Scenarios 1.1 and 1.2 only yield a limited emission reduction compared to the other scenarios while it has the smallest cost. The first scenario is more efficient however, at around 682 SEK/ton compared to 918 SEK/ton, due to that the cost is doubled when the extended sorting facility is includeed while the emission reduction only increases slightly.

For the requirement specification scenarios, the relative costs are lower than the scenarios only considering sorting. Scenario 2.1 range between 79 – 97 SEK/ton and for 2.2 the range is 150 – 198 SEK/ton. The strict requirement specification of the fuel yields both increased income and an emission reduction that, by design of this study, is capable to off-set the emissions added by Lövsta. As both scenarios were designed to achieve a similar level of emission reduction, scenario 2.1 is more cost efficient due to its lower cost. 2.2 does on the other hand allow for a more lenient requirement specification of the fuel, as the extended sorting gives more room for plastics in the SRF-streams. This could potentially mean that SE would be likelier to negotiate such a deal with a delivering partner than the more hard-lined requirement specification in scenario 2.1.

The greatest range of cost efficiency is found among the CCS scenarios. As the amount of abated CO_2 is by far the most in the scenario with CCS at KVV-8, the relative emission reduction cost becomes the smallest at 23 SEK/ton, for scenario 3.1 with incentives. As the incentive covers all the costs for the CCS in this case, the only cost comes from the sorting cost included in all other scenarios. Without incentives the cost is instead much greater, ranging between 637 – 913 SEK/ton. CCS at KVV-8 is then a significant risk, it would make SE dependent on incentives to cover its costs. For scenario 3.2 the relative cost is much higher, ranging between 421 – 506 SEK/ton with incentives and 1272 – 1545 SEK/ton without incentives. The cost increase compared to 3.1 stem from a few different reasons. Mainly, smaller quantities of CO_2 are captured at Lövsta than at KVV-8, about 587 kton instead of the assumed 850 kton for KVV-8. This expectedly makes the net decrease of CO_2 emissions from the reference case smaller and raises the relative cost. The received incentives do only cover 68% of the expenses due to that the share of biogenic CO_2 captured at Lövsta is 68%, instead of the 100% biogenic CO_2 captured at KVV-8. The fossil share of the captured CO_2 results in lower costs for EUA though, as discussed above.

The income for each scenario relative to the reference case is also analyzed. In figure 11 we see the difference between a scenario's total income and the income for the reference case for the same cost case. The income in this analysis refers to the income from gate fees as well as the net decrease cost of EUA for a scenario, thus the relative income shows how much more income is generated in a scenario due to the extra waste used as fuel and the decrease of CO_2 emissions. This is helpful to deduce to what extent the scenarios can "pay for themselves", as the relative income is how much the income is increased due to the implementation of the studied measures.

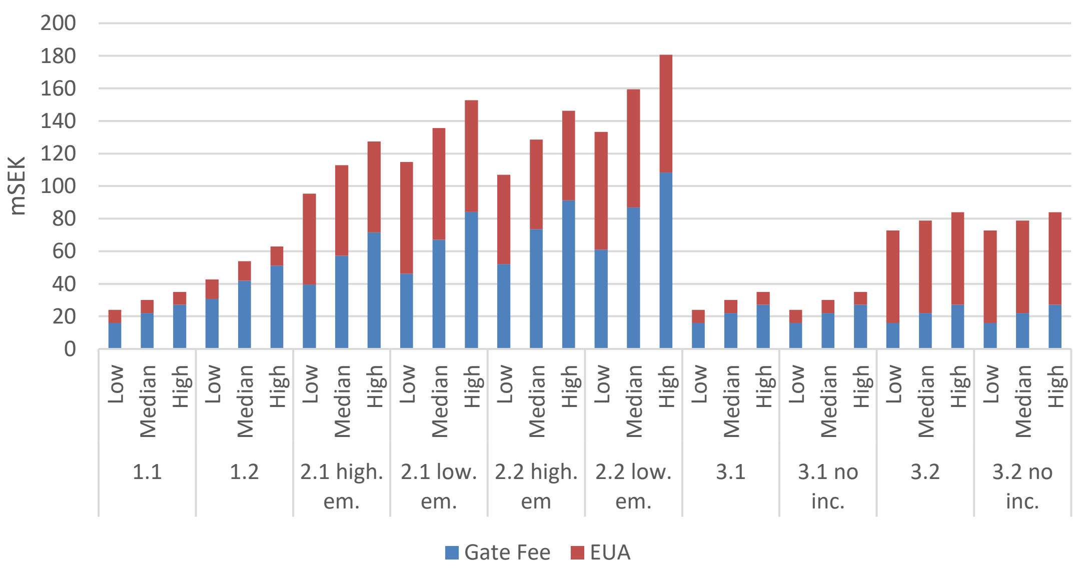

Figure 11: Relative income for each scenario compared to the reference case, given in mSEK.

Note that here the income cases low, median, and high refers to when the gate fee and the free allocation of EUA credits are low, median, and high, respectively. This contrasts with previous use of the incomes in table 20, where low incomes were used in the cases for high costs. Additionally, the cost for EUA was used as a cost in those previous comparisons, here they are used for the relative income as the lower cost of the scenarios is a net negative cost compared to the reference case.

For scenarios 1.1 and 1.2, all additional income is related to the sorting, either as the income gained from gate fees for the waste that compensates the loss of LHV or as reduced EUA costs due to emission reduction. As the reduction of emission is relatively small, the reduced EUA costs only make up a small share of the relative income. As stated in 3.5.1, the waste sorted in a facility paid for by SE generates a gate fee, adding to the total income from gate fees even if the waste is not thereafter used as fuel. This is a further explanation to why the income from gate fees is as large compared to the EUA incomes. The ranges of the incomes are 24 – 35 mSEK for scenario 1.1 and 43 – 63 for scenario 1.2.

For the requirement specification scenarios, the incomes become much greater, due to the large quantities of fuel needed as the fuel has a lower heating value and the considerable decrease of emissions. The range for 2.1 (high) is 95 – 127 mSEK, for 2.1 (low) 115 – 153 mSEK, 107 – 146 mSEK for 2.2 (high) and 133 – 181 for 2.2 (low). The relative income from reduced EUA costs becomes more on par with the income from gate fees, as the measure here gives a considerable emission reduction.

The incomes for scenario 3.1 is identical to scenario 1.1, as it in practice has the same properties as the first scenario. As the emission reduction effort of the BECCS plant in KVV-8 only generates negative emissions, none of these can be counted towards the decrease in cost for EUA, as that only takes actual fossil emissions into consideration. The income solely comes from what can be generated from the emission reduction and additional fuel required due to the sorting facilities. For scenario 3.2 it is different, since a CCS facility reduces the actual amount of fossil CO_2 emitted from the plant. The share of the relative income related to reduced EUA costs becomes much greater to that of the generated gate fee, since the only additional waste used as fuel for this scenario is due to the sorting. The range of the incomes for scenario 3.2 is 73 – 84 mSEK.

5. Discussion

This chapter is dedicated to discussing the results described above in relation to the aim and puspose of this study.

5.1 Accuracy of the model

Some factors of the methods accuracy in representing the real emissions and economic aspects deserve some further detailing. As discussed in chapter 4.1.2, the method for determining LHV yield a value that could be regarded as high for the initial compositions of the SRF waste. It is reasonable to assume that this also carries over in some degree to the constructed SRF compositions. The difference between the calculated LHV values and the estimations that have been used as reference derives from that the SRF wastes LHV was estimated with a different method in the reference. The utilization of the mathematical method in this study was decided on for comparability between the estimations of all compositions, and the estimation of the MSW compositions yielded a value that was much closer to the reference values. As the LHV is used to define the quantities needed to achieve the design parameter of the energy quantity of the streams, a high value could be regarded as a conservative estimation as a high LHV results in smaller quantities of waste which in turn lead to a smaller generated gate fee than from a stream with a lower heating value. Due to this the method used to define the LHV for the stream is deemed to be reasonably accurate.

Related to determining LHV for the streams and also fundamental to estimate the emissions from each stream is the method to establish the elemental composition for each stream. The accuracy for this method relies on the reliability of the data material for the elemental shares of each fraction as of tables 3-4. There have been no reason to distrust the data set, though as they are fundamental for the precision of all models used, it is suitable to recognize that some degree of inaccuracy in the data set could affect the results. For further utilization of the model however, the accuracy should only increase if the data set is more well defined and by knowing more about the fractions used to define the streams. In the same vein, increasing the availability of picking analysis on the waste that is used as fuel would also improve the accuracy, especially for the C&I waste where no analysis were available and assumptions had to be made.

Other sources of inaccuracies are the assumption that all coal in the fuel is oxidized into CO_2 when combusted, which would not necessarily be certain in a real combustion. The same assumption have been made in other similar studies, why it should be reasonable to adopt the same simplification for this study (Avfall Sverige Utveckling, 2012, p 10). The potential for capture for the calculations regarding CCS could certainly also be improved if more site-specific parameters could be accounted for.

5.2 Off-set of Lövsta

As mentioned in 4.2.1, both scenarios only including sorting fail to offset the emissions from Lövsta, but as sorting is included in the other scenarios the emission reduction due to the sorting does help towards offsetting the added emissions. The requirement specification scenarios manage to offset Lövsta, but apparent from the comparison of utilization of different streams in tables 16-19 is that expectedly the most important factor is to limit the emissions derived from Lövsta. All combinations of streams utilized in Högdalen are unable to offset the Lövsta emissions for all comparisons when the Lövsta stream contain 10% plastic or more. As detailed in table 17 and 19, where the fuel in Lövsta contain no plastic, almost all combinations yield a net decrease of emissions significant enough to offset Lövsta. If no other measures than sorting and requirement specification are included, then limiting the fossil fractions of the fuel for Lövsta is a necessity if the ambition to remain at pre-Lövsta emissions should be upheld after the opening of the Lövsta facility.

The scenarios 2.1 and 2.2 represented when the requirement specification included the emission reduction from the already planned sorting and the extended sorting, respectively. The significance of extended sorting depends on how successful SE will be in reaching an agreement with a supplier of SRF fuel to limit the share of plastics. The requirement specified constitutions of the SRF presented in figures 4-5 was made without regard to if any constitution would be likely that a supplier of SRF would agree to, and no account have been made to how such agreements are made and what would be unrealistic. In reality the combinations of requirement specified streams, as presented in tables 16-19, could possibly not all be feasible. If for instance SE would be unsuccessful in convincing any supplier of SRF waste to limit the share of plastics to a maximum of 5%, then all combinations with streams containing no plastics would be impossible. Such a scenario is represented in table 16, where the Swedish SRF fuel used at Högdalen is required to contain no plastics to yield any combination of streams that can offset Lövsta. With the same reasoning none of the cases where the fuel for Lövsta is set to 0% plastics would be feasible. If such a restriction would exist, requirement specification without extended sorting would be unable to offset Lövsta. If there is no restrictions to what the requirement specified streams would be however, extended sorting would instead be superfluous to offset Lövsta. The cases where any of the considered streams contain no plastic all succeed to offset Lövsta in the extended sorting scernario. When the Lövsta fuel contain no plastic there is a significant overshoot in how much the emission reductions can offset Lövsta, ranging between 141,4% – 310,5%. Considering that the cost efficiency for requirement specification with extended sorting performs worse than requirement specification without the extended sorting and that there is a greater uncertainty for the cost, it would be more cost effective to offset Lövsta with a strict requirement specification without extending the sorting capabilities if SE are able to. The cost efficiency and cost uncertainty for the extended sorting is discussed further in 5.3.

It should be noted that regardless of if extended sorting is included or not, the necessary limitations of plastic in the SRF fuel through requirement specification could be regarded as extensive. The cutoff point for if an offset is possible through requirement specification is the combination of streams highlighted below in table 21. The combinations can also be found in tables 16 and 18. Note that two distinct combinations of utilized streams have been highlighted for the extended sorting, this is because while *"extended sorting 1"* is the combination that fulfills the condition to offset Lövsta with the least overshoot from how much aggregated emission reduction that is needed, *"extended sorting 2"* is at a similar level while it utilizes a different combination of streams to the previous example. It is useful to highlight that different combinations of streams can fulfill the requirement. Both extended sorting 1 and extended sorting 2 can be found in table 18.

Table 21: Percentage of plastic allowed in the streams for an offset of the Lövsta emsissions to be possible.

Stream and plant	Planned sorting	Extended sorting 1	Extended sorting 2
Imported SRF (Högdalen)	<5	<15	0
Swedish SRF (Högdalen)	0	<5	<10
Imported SRF (Lövsta)	<5	<5	<5
Resulting offset	105,0	101,1	101,5

If any of the streams in the combinations above would contain more plastic, offsetting the emissions from Lövsta would not be possible. As all combinations require at least one stream to be limited to at most 5% plastics, this presents the boundaries to whether offsetting Lövsta only through sorting and requirement specification is a feasible solution. If SE would find that no supplying partner would agree to providing a fuel with 5% plastics or less, these measures would not be sufficient to offset Lövsta on their own, and other measures such as CCS would be required to fulfill the condititon.

As both studied scenarios where CCS have been implemented yield net negative emissions with all streams summarized, the measures ability to offset Lövsta is self-explanatory. Both for when the CCS technology is implemented on KVV-8 or Lövsta, no requirement specification of any streams was included.

5.3 Cost efficiency

As presented in chapter 4.4, the scenarios that perform best in terms of cost efficiency for the achieved reduction of fossil emissions are the requirement specification scenarios 2.1 and 2.2. As the measure have no direct costs tied to the emission reduction this is not surprising. The only costs included for 2.1 and 2.2 in figure 10 are the same carried over costs as from the sorting scenarios 1.1 and 1.2. The interesting question for the cost efficiency for requirement specification is what the effect it could have on the gate fee SE acquires for the received waste. As the supplier of SRF waste assumingly still would have a need to dispose of the material rejected by SE and that this could lead to some extra costs for the supplying partner, it is a reasonable assumption that this would affect the gate fee negatively, both to cover any potential cost and for the fact that SE wouldn't provide as of an desirable service for the supplier. This study has taken no measure of to what degree the gate fee could be affected in such a matter. One factor that speaks positively for SE however are that the requirement specification scenarios account for significant incomes even in the high cost scenarios. Table 20 show that all cost cases of the scenarios 2.1 and 2.2 have a net income after all cost are accounted for, including the "high cost scenarios" where the by Profu estimated gate fee is set to the lowest estimation. That all cases are profitable is an indicator that SE could shoulder a drop of the value of the gate fee. However, to give a rough comparison of the the scenarios if we assume that requirement specification will affect the value of the gate fee, the net profit from the median reference case can be compared with the high cost case for 2.1 and 2.2. As the median case yields a profit of 403,8 mSEK, and the net profits for the high cost cases for the requirement specification scenarios ranges between 306,7 – 334,9 mSEK, this gives a loss of 68,9 – 97,1 mSEK, if we assume that the value of the gate fee is reduced due to the requirement specification and that the value otherwise wouldn't have been affected. This is only a rough estimation as the cost cases include other differences than the value of the gate fee, such as the price for the EUA-credits.

The measure of sorting is seemingly not very cost efficient in terms of achieved emission reduction. The emission reduction granted by the sorting facilities is not high compared to the other measures and the costs are significant. Expectedly the cost efficiency worsens with the inclusion of the extended HSMA facility in scenario 1.2, as this is assumed to lead to an added cost equal to the cost for the BOSS facility. However, if the income increase relative to the reference case is factored in, the cost efficiency looks much better for the sorting scenarios. As shown in figure 11, the relative income from gate fee and reduced EUA costs to the reference case give a range of income of 24-35 mSEK for scenario 1.1 and 43-63 mSEK for 1.2. This income, a result of the extra waste needed to uphold the energy quantity of the plant and of the reduced emissions, is comparable to the costs for the sorting facilities, 20,4 mSEK for 1.1 and 40,8 for 1.2. Unlike with the scenarios for requirement specification, there is no reason to assume that the sorting would affect the price of the gate fee. The sorting facilities could therefore be regarded to be cost effective as the additional income compensate for the cost. As the estimation for the cost for the extended sorting facility adjacent to HSMA is the cost estimation with the most uncertainty, it is still reasonable to be skeptical to whether the additional income would be sufficient to pay for the facility.

The cost efficiency for scenarios 3.1 and 3.2 regarding CCS implementation without incentives perform similarly in cost efficiency to the sorting scenarios but for the opposite reason. They are the scenarios that by far reduces emissions the most but also dwarfs the others in direct costs. 3.1 performs better than 3.2, as greater negative emissions can be achieved and the cost for capture, gathered directly from an SE report on the facility, is significantly lower than the more general cost estimation for capture used for the Lövsta facility. If incentives are included however, 3.1 have the best cost efficiency of all scenarios. As the incentive cancels out any costs related to capture, transport and storage of biogenic CO_2, the only cost related to the scenario is the carried over costs from the planned sorting. The relative income to the reference case is the same as for the planned sorting scenario as well, as the incentive is not counted among the incomes that are described in chapter 3.5.7. This highlight the dependency SE would have on external incentives to make an implementation of CCS on KVV-8 a valuable solution. When no incentives are added to 3.1, it only achieve a net income for the lowest cost case as seen in table 20. For 3.2 the situation is even more difficult. The cost is greater than for 3.1 and as the fuel in Lövsta is a mix of biogenic and fossil the incentives would only be available for the biogenic share of the captured CO_2. Even as shown in figure 11 the relative income related to the reduced EUA cost increases greatly, thanks to that fossil CO_2 is captured at Lövsta, the costs greatly outweigh the incomes. Even with incentive, 3.2 fail to achieve a substantial net income, where the low-cost case performs at similar levels as other scenarios high cost cases. If incentives are unavailable the scenario fail to produce a net income for all of the cost cases. Regarding the conclusions drawn from the cost efficiency of the requirement specification scenarios, he cost efficiency for 3.2 could be improved by similar measures to the fuel at Lövsta as done for scenarios 2.1 and 2.2. The income from acquired gate fee would increase, and the possible incentives would increase as well as the fossil share of the fuel would be smaller. This however goes against one of the points with implementing CCS in the first place, as it can be seen as a reliable way to reduce the emissions without having to take any other measures. As described above, requirement specification without any regards to its plausibility is capable to achieve the goal to offset Lövstas emissions, but if any of the circumstances described in 5.2 would make requirement specification on its own unfeasible, then CCS could be what is required to fulfill the condition. In that case however, an implementation on KVV-8 seems to be the more profitable solution.

5.4 Practicality of the proposed measures

As both HSMA and BOSS are in the developing phase, the realization of the sorting measures as of scenario 1.1 is the highest of the proposed scenarios. Though, as discussed above, the real possibility for sorting to affect how Lövsta’s emissions can be offset is by combining it with requirement specification. The extended sorting as of scenario 1.2 requires further investigation if it would be realized. Firstly, it needs to be investigated whether it is plausible that construction of such a facility could be made. For this study, an extension of the prior sorting facilities have been a hypothetical case, if it were to be made into real plans investigations for available space for a facility for example would have to be made. The cost of such a facility should also be estimated more thoroughly. As shown by the imagined case in this study, whether realization of such plans are necessary is questionable.

The feasibility of requirement specification as suggested by this report have been discussed previously, with the most important factor to consider being reaching agreements with suppliers of waste to the specifications desired. It could possibly require SE to extend its network of suppliers of SRF waste, whether that could lead to costs for SE is not investigated in this report. One practical factor not discussed previously is whether it is reasonable to assume, as have been done for this study, that SE can freely combine streams of imported SRF with varying compositions in the Högdalen and Lövsta facilities as have been done to find the optimal combinations detailed in 4.2.3. If SE are limited to a single supplier of waste for the imported SRF waste, it could be a likely scenario that the supplier only would supply one composition of the fuel. This would restrict the possible combinations of fuel utilization in Högdalen and Lövsta similarly to what was discussed in 5.2. Diversifying the suppliers of imported SRF waste could therefore be a priority for SE.

This study has not made any effort to investigate the feasibility of implementing CCS technology on either KVV-8 or Lövsta but have worked from the assumption that it would be possible. As it would be a significant remodeling of the considered facilities it is not certain that it would be a feasible solution. For KVV-8, the previous internally made study and the ongoing pilot speaks for its feasibility. For Lövsta more have to be investigated in terms of the technical feasibility of an implementation.

5.5 Further studies

This study has only regarded the local emissions from the facilities run by SE. To accurately estimate what effect the proposed measures would have on global warming and the larger network of suppliers of waste, global emissions should be investigated further. Primarily the measure of requirement specification deserves to be investigated to what extent the application of the measure at SE affect global emissions, as the rejected waste will have another trajectory when SE no longer is the end destination. Interesting topics would be if an actor like SE could affect the generation of plastic waste in society at large if they decide to exclude plastics from their fuel. Potential models to investigate such a network impact could be with the theories regarding technological push and demand pull. A related topic is how sorting can affect the material recycling rates when more material is available for recycling.

6. Conclusion

The purpose of this study was to investigate the effectiveness and cost efficiency of sorting of MSW, requirement specification, and implementation of CCS technology to achieve a reduction of fossil CO_2-emissions sufficient to offset the emissions of a facility for waste incineration under development in Lövsta. To investigate this, the emission reduction potential and their associated costs of each of the measures was established, with particular care in specifying how the desired levels of emissions could be achieved through requirement specification, as choosing to what degree the fossil fractions of waste should be limited in each relevant waste stream is a question of optimization.

The results showed that having sorting of MSW as the only measure to reduce emissions cannot achieve an emission reduction sufficient to offset Lövsta, as the quantities of the MSW waste puts a limitation on how high the sorting capacity can become. Cost efficiency for sorting is on the other hand good, as the costs for sorting is covered by the additional income from the extra waste needed to uphold the energy output as the waste is sorted.

The desired emission reduction can be achieved with a combination of sorting and requirement specification, but only if the waste used as fuel at the Lövsta facility is limited to at most 5% plastics. The plastic share of the other streams of SRF waste used as fuel at the Högdalen facility must also be limited to achieve an emission reduction sufficient to fulfill the condition, to at most 15% allowed plastics in the imported SRF stream, when the emission reduction from an extended sorting is included. This could be problematic, as requirement specification as a measure relies on whether SE can reach an agreement with a supplier that can provide waste with such specifications. It could also affect the price of the gate fee SE would receive per ton waste. Economically, requirement specification is the measure that performs the best, as there are no additional cost and the incomes from gate fees and decreased costs for EUA are significant. If the price of the gate fees is affected by the requirement specification, the results show that SE would make a net profit of 306,7-334,9 mSEK depending on the scenario for the high cost case.

Implementation of CCS technology would produce negative emissions enough to not only offset Lövsta but yield net negative emissions for all studied facilities. This should however be considered highly risky in economic terms, as SE would become dependable on incentives of the technology. With incentives to implement the technology at the KVV-8 facility, it provides the most cost-effective alternative as the measure in that case would be considered cost free. The case where SE receives no incentives for KVV-8 however shows that there could be unsignificant profits to significant losses. For CCS on Lövsta, the lowest cost case only yields a profit comparable to the highest cost case for the requirement specification, while without incentives it would be altogether not profitable.

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Appendix A

Composistion of the streams in tables

In the study, the composition of the streams in dry was presented in diagrams, while the composition in ar was not presented altogether. Here the percentages of each fraction are presented in numerical form to increase transparency of the data that was fundamental to the calculations of this study. The data for the tables are the same as have been presented in the study. The diagram related to the composition of MSW in ar is found in 3.2.2, gathered from Lundin (2016), Vukicevic (2016) and Silferduk et al., (2017). The diagrams showing the composition for SRF in dry is found in 4.1.1, gathered from Lindman (2019). The transformations between ar and dry was made utilizing the methods presented in 3.2.6.

Composition in as received

As described in the report, the composition in ar was used to find the streams that fulfilled the target of allowed quantity of a fraction for the sorted and requirement specified streams, i.e the share of plastics for the <5% plastic streams of the SRF waste must be <5% for the ar composition. The shares have been rounded off to the first decimal.

Table 22: Percentages for fractions for imported SRF waste streams in ar.

	Original	<20%	<15%	<10%	<5%	0%
Plastics	22,3	19,5	14,3	9,6	4,4	0
Wood	31,6	34,6	36,8	38,9	41,1	43,0
Organic waste	0	0	0	0	0	0
Paper	29,1	31,9	34,0	35,9	37,9	39,7
Metal	1,8	1,9	2,0	2,2	2,3	2,4
Rubber	1,9	2,1	2,2	2,3	2,5	2,6
Textile	7,8	3,8	4,1	4,3	4,6	4,8
Combustibles	1,4	1,5	1,6	1,7	1,8	1,9
Non-comb.	4,2	4,6	4,9	5,2	5,5	5,7

Table 23: Percentages for fractions for Swedish SRF waste streams in ar.

Fraction	Original	<15%	<10%	<5%	0%
Plastics	18,8	14,8	9,4	4,4	0
Wood	36,6	38,4	40,9	43,1	45,1
Organic waste	0	0	0	0	0
Paper	28,3	29,6	31,5	33,3	34,8
Metal	2,2	2,3	2,4	2,6	2,7
Rubber	2,1	2,2	2,3	2,5	2,6
Textile	6,7	7,1	7,5	7,9	8,3
Combustibles	1,1	1,2	1,3	1,3	1,4
Non-comb.	4,2	4,4	4,7	4,9	5,1

Table 24: Percentages of fractions for MSW streams in ar.

Fraction	MSW	MSW Högdalen	MSW Brista
Plastics	15,1	5,1	4,8
Wood	0,1	0,1	0,1
Organic waste	32,6	26,4	31,0
Paper	17,4	23,5	22,0
Metal	1,6	0,2	0,2
Rubber	0	0	0
Textile	0,5	0,6	0,6
Combustibles	24,1	32,4	30,4
Non-comb.	8,7	11,7	11,0

Composition in dry

These tables correspond to figures 4 – 6 in chapter 4.1.1. The percentages have been rounded off to the first decimal.

Table 25: Percentages of fractions for the imported SRF waste streams in dry.

	Original	<20%	<15%	<10%	<5%	0%
Plastics	20,5	18,1	13,2	8,8	4,0	0
Wood	36,1	39,8	42,2	44,3	46,6	48,6
Organic waste	0	0	0	0	0	0
Paper	24,9	27,4	29,1	30,5	32,2	33,5
Metal	1,5	1,7	1,8	1,8	1,9	2,0
Rubber	2,3	2,5	2,7	2,8	3,0	3,1
Textile	9,2	4,6	4,8	5,1	5,3	5,6
Combustibles	1,2	1,3	1,4	1,5	1,6	1,6
Non-comb.	4,2	4,6	4,9	5,2	5,4	5,6
Moisture	24,0	24,4	24,0	23,7	23,3	23,0

Table 26: Percentages of fractions for the Swedish SRF waste streams in dry.

Fraction	Original	<15%	<10%	<5%	0%
Plastics	17,1	13,4	8,5	4,0	0
Wood	41,5	43,4	45,9	48,1	50,1
Organic waste	0	0	0	0	0
Paper	23,9	25,0	26,4	27,7	28,9
Metal	1,8	1,9	2,0	2,1	2,2
Rubber	2,5	2,6	2,8	2,9	3,0
Textile	7,9	8,3	8,7	9,2	9,5
Combustibles	1,0	1,0	1,1	1,1	1,2
Non-comb.	4,1	4,3	4,6	4,8	5,0
Moisture	23,3	23,0	22,5	22,1	21,7

Table 27: Percentages of fractions for the MSW streams in dry.

Fraction	MSW	MSW Högdalen	MSW Brista
Plastics	18,4	6,0	5,8
Wood	0,1	0,2	0,1
Organic waste	19,9	15,6	18,8
Paper	19,8	25,8	24,8
Metal	1,8	0,2	0,2
Rubber	0	0	0
Textile	0,7	1,0	0,9
Combustibles	27,7	36,2	34,8
Non-comb.	11,5	15,0	14,4
Moisture	42,7	40,9	42,4

Appendix B

Aggregated emission reduction comparisons

In chapters 4.2.2 – 4.2.3 in the report, the comparisons for the aggregated emission reductions, derived from sorting and requirement specification, only presented the results from comparisons with the fuel at Lövsta containing 5% or 0% plastics. Those were the only comparisons that yielded a reduction of more than 100% of the emissions from Lövsta, why they are the only comparisons of real importance to this study. For transparency are the other comparisons detailed below.

Aggregated emission reduction for planned sorting

Here are the comparisons to emissions from Lövsta with 20 – 10% plastics in the fuel, when the contribution from sorting are from the planned sorting.

Table 28: The percentage of the aggregated emission reduction from planned sorting and requirement specification on the fuel for the Högdalen site to the emissions from Lövsta with a maximum of 20% plastics in the fuel.

		Imported SRF					
		Original	<20%	<15%	<10%	<5%	0%
Swedish SRF	Original	14,7	15,3	16,9	18,5	20,4	22,2
	<15%	18,2	18,7	20,3	21,9	23,9	25,7
	<10%	23,3	23,8	25,4	27,0	28,9	30,7
	<5%	28,4	29,0	30,6	32,2	34,1	35,9
	0%	33,5	34,0	35,6	37,2	39,1	40,9

Table 29: The percentage of the aggregated emission reduction from planned sorting and requirement specification on the fuel for the Högdalen site to the emissions from Lövsta with a maximum of 15% plastics in the fuel.

		Imported SRF					
		Original	<20%	<15%	<10%	<5%	0%
Swedish SRF	Original	18,3	19,0	21,0	23,0	25,4	27,6
	<15%	22,6	23,3	25,3	27,3	29,7	31,9
	<10%	28,9	29,6	31,6	33,5	36,0	38,2
	<5%	35,4	36,0	38,0	40,0	42,4	44,6
	0%	41,6	42,3	44,3	46,2	48,6	50,9

Table 30: The percentage of the aggregated emission reduction from planned sorting and requirement specification on the fuel for the Högdalen site to the emissions from Lövsta with a maximum of 10% plastics in the fuel.

		Imported SRF					
		Original	<20%	<15%	<10%	<5%	0%
Swedish SRF	Original	24,1	25,0	27,6	30,2	33,4	36,3
	<15%	29,8	30,7	33,3	35,9	39,1	42,0
	<10%	38,1	38,9	41,6	44,2	47,3	50,3
	<5%	46,6	47,4	50,1	52,6	55,8	58,8
	0%	54,8	55,7	58,3	60,9	64,0	67,0

Aggregated emission reduction for extended sorting

Following are the comparisons for when the extended sorting has been used.

Table 31: The percentage of the aggregated emission reduction from extended sorting and requirement specification on the fuel for the Högdalen site to the emissions from Lövsta with a maximum of 20% plastics in the fuel.

		Imported SRF					
		Original	<20%	<15%	<10%	<5%	0%
Swedish SRF	Original	21,9	22,4	24,0	25,6	27,5	29,3
	<15%	25,3	25,9	27,5	29,0	31,0	32,8
	<10%	30,4	30,9	32,5	34,1	36,0	37,8
	<5%	35,6	36,1	37,7	39,3	41,2	43,0
	0%	40,6	41,1	42,7	44,3	46,2	48,0

Table 32: The percentage of the aggregated emission reduction from extended sorting and requirement specification on the fuel for the Högdalen site to the emissions from Lövsta with a maximum of 15% plastics in the fuel.

		Imported SRF					
		Original	<20%	<15%	<10%	<5%	0%
Swedish SRF	Original	27,2	27,9	29,9	31,8	34,2	36,5
	<15%	31,5	32,2	34,7	36,1	38,5	40,8
	<10%	37,8	38,4	40,4	42,4	44,8	47,0
	<5%	44,2	44,9	46,9	48,8	51,3	53,5
	0%	50,5	51,1	53,1	55,1	57,5	59,7

Table 33: The percentage of the aggregated emission reduction from extended sorting and requirement specification on the fuel for the Högdalen site to the emissions from Lövsta with a maximum of 10% plastics in the fuel.

		Imported SRF					
		Original	<20%	<15%	<10%	<5%	0%
Swedish SRF	Original	35,8	36,7	39,3	41,9	45,1	48,0
	<15%	41,5	42,4	45,0	47,6	50,8	53,7
	<10%	49,7	50,6	53,2	55,8	59,0	61,9
	<5%	58,2	59,1	61,7	64,3	67,5	70,4
	0%	66,4	67,3	69,9	72,5	75,7	78,6