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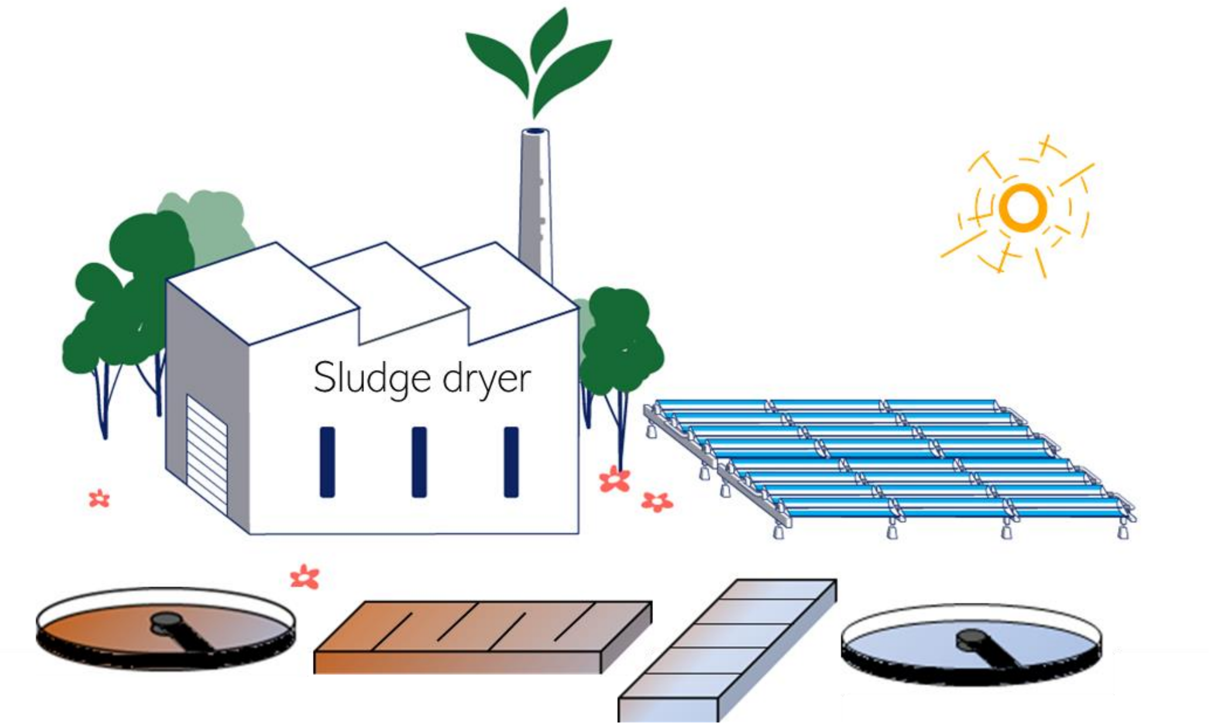

Using Solar Thermal Energy in the Sludge Drying Process of a Wastewater Treatment Plant

A case study of Kattastrand WWTP in Härnösand, Sweden

Master's thesis in the Master's Programme Infrastructure and Environmental Engineering

ISAK SVENSSON

Department of Architecture and Civil Engineering
Division of Water Environment Technology

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021
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MASTER'S THESIS ACEX030

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Isak Svensson

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Examensarbete ACEX30
Institutionen för arkitektur och samhällsbyggnadsteknik
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Cover: Illustration of a wastewater treatment plant with solar thermal powered wastewater sludge drying

Gothenburg, Sweden, 2021

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Abstract

Wastewater sludge is produced wherever humans live and is one of the final fractions of conventional wastewater treatment. The wastewater sludge is commonly used in agriculture as a fertilizer, disposed in landfills, incinerated or used for plant soil production but this varies by country and region based on legislation, management trends and regional conditions. Newly proposed legislation in Sweden suggests a ban on the use of wastewater sludge in agriculture as it contains pollutants that could pose a risk for the environment and human health. In combination with the suggested ban a requirement for phosphorus recycling is suggested as wastewater sludge contain lots of nutrients that otherwise would be lost. The public inquiry suggests two technology chains for the new management that is required and in both these technology chains sludge drying is a key a process. Thermal sludge drying is also a recommended hygiene treatment method and will result in more efficient transportation due to volume and mass reduction of the sludge. But as thermal drying requires large amounts of energy it is essential to evaluate sustainable sludge drying alternatives to be able to meet commitments regarding greenhouse gas emissions. This thesis is evaluating the potential of using solar thermal energy in the sludge drying process and is designed as a case study for a specific wastewater treatment plant in Härnösand in northern Sweden. Feasibility is evaluated by conducting a cost-benefit analysis for the identified scenarios and compared with the zero alternative which is the current management for the specific treatment plant. The results show large potential in using solar thermal energy in sludge drying but due to large emissions related to the intermediate sludge storage required since solar energy is only available during the summer in Sweden the most profitable alternative is to have multiple energy sources to be able to conduct continuous operation of the drying process. The results in this thesis should be viewed as potential cost for the society as a whole and further optimization of the economics is recommended before implementation.

Keywords: wastewater sludge, solar thermal energy, sludge drying, cost-benefit analysis, wastewater sludge management, sustainability, greenhouse gas emissions

Användning av termisk solenergi i slamtorkningsprocessen i ett avloppsreningsverk

En fallstudie av Kattastrand reningsverk i Härnösand, Sverige

Examensarbete inom mastersprogrammet Infrastruktur och Miljöteknik

ISAK SVENSSON
Institutionen för arkitektur och samhällsbyggnadsteknik
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Sammanfattning

Avloppsslam produceras överallt där människor bor och är en av slutfraktionerna efter konventionell avloppsrening. Avloppsslam används vanligtvis i jordbruket som gödsel, deponeras, förbränns eller används för produktion av anläggningsjord men detta varierar beroende på land och region baserat på lagstiftning, hanteringstrender och regionala förhållanden. Utredningen om hållbar slamhantering presenterade ett förslag till ny lagstiftning där man vill införa ett förbud mot användning av avloppsslam i jordbruket eftersom det innehåller föroreningar som kan utgöra en risk för miljö och människors hälsa. I kombination med det föreslagna förbudet föreslås ett krav på återvinning av fosfor eftersom avloppsslam innehåller mycket näringsämnen som annars skulle gå förlorade. Den offentliga utredningen föreslår två teknologikedjor för den nya hanteringen av avloppsslam och i båda dessa teknologikedjor är slamtorkning en nyckelprocess. Värmebehandling och torkning är också en rekommenderad metod för hygienbehandling av avloppsslam och kommer att resultera i effektivare transport på grund av volym och massreduktion av slammet. Men eftersom värmetorkning kräver stora mängder energi är det viktigt att utvärdera hållbara slamtorkningsalternativ för att kunna uppfylla åtagandena om växthusgasutsläpp. Denna avhandling utvärderar potentialen för att använda solvärme i slamtorkningsprocessen och är utformad som en fallstudie för ett specifikt avloppsreningsverk i Härnösand i norra Sverige. Genomförbarheten utvärderas genom en kostnads-nyttoanalys för de identifierade scenarierna som jämförs med ett referensalternativ vilket är den nuvarande slamhanteringen för det specifika reningsverket. Resultaten visar stor potential i att använda solvärme vid slamtorkning men på grund av stora utsläpp relaterade till det mellanlagring av slam som krävs eftersom solenergi endast finns tillgänglig under sommaren i Sverige är det mest lönsamma alternativet att ha flera energikällor för att kunna genomföra kontinuerlig drift av torkningsprocessen. Resultaten i denna avhandling ska ses som en potentiell kostnad för samhället som helhet och ytterligare optimering av ekonomin rekommenderas före implementering.

Nyckelord: avloppsslam, solvärme, slamtorkning, kostnadsnyttoanalys, avloppsslamhantering, hållbarhet, växthusgasutsläpp

Acknowledgement

This Master's thesis was the final part of my civil engineering studies at Chalmers University of Technology. The work was carried out from December 2020 to June 2021 in cooperation with Absolicon Solar Collector AB.

I would like to thank my supervisor Professor Britt-Marie Wilén and Jonatan Mossegård, technical manager at Absolicon, for valuable guidance and advice. I also want to express my gratitude to Härnösand Energi & Miljö AB which has assisted with valuable information. Additional thanks to Carlo Semeraro at Absolicon and Pontus Hallbäck at HUBER and all other helpful people that contributed to the results of this work.

Isak Svensson, Gothenburg, 2021.

Content

Abbreviations and definitions

WWTP – Wastewater treatment plant
PE – population equivalent: Corresponds to the amount of biodegradable materials that have a biochemical oxygen demand of 70 grams of dissolved oxygen per day for seven days (BOD_7)
Large wastewater treatment plant – A WWTP with more than 2000 pe connections
DS – Percentage of weight of dry substance
HEMAB – Härnösand Energi & Miljö AB
Absolicon – Absolicon Solar Collector AB
EPA – Environmental Protection Agency
DNI – Direct Normal Irradiance
CHP – Combined Heat and Power plant
NPV – Net present value
MSEK – Millions Swedish kronor
SEK – Swedish krona

1 Introduction

Climate change is considered the greatest threats to human health in the 21st century (WHO, n.d.). Countries, organizations, and companies all over the world are taking action to reduce the greenhouse gas emissions as well as implementing new policies and strategies to help tackle the problem ahead and to be able to reach the ambitious target reductions that are set all sectors must participate in the change. This paper will investigate the possibility to use solar thermal energy in the sludge drying process of a wastewater treatment plant (WWTP) in Härnösand in northern Sweden, as well as evaluate the feasibility of possible solutions that is found in a technical, economical and sustainability perspective.

1.1 Background

In 2015 at the United Nations (UN) Sustainable Development Summit in New York the UN and its member states decided to adopt the 2030 Agenda for Sustainable development and its 17 Sustainable Development Goals (UN, 2015b). Which is considered a blueprint for peace and prosperity for people and the planet today and for future generations. On the same year, the Paris Agreement on Climate Change was agreed upon which is a legally binding treaty to limit global warming to well below 2, preferably to 1,5 degrees Celsius and which has laid the foundation of environmental and climate policies around the world (UN, 2015a).

Sweden has actively taken a leading role in the implementation of the 2030 Agenda and the fight against climate change by appointing a special committee of inquiry to follow up, review and to continuously develop proposals for advancing the implementation of the agenda (SOU 2019:13). In addition to this, in 2017, Sweden adopted a new climate policy framework with specific climate targets with the long-term goal of having zero net greenhouse gas emissions by the year 2045 (The Swedish EPA, 2017). In the Swedish Government guidelines for a sustainable and cycle-adapted water and sewerage system it is stated that operations and maintenance of WWTPs should not produce air emissions that is of harm to the environment and that the use of non-renewable energy sources should be minimized (Prop. 1997/98:145). The same proposition has also formulated the goals that future sewage systems should be designed in a way that enables a closed nutrition cycle between the society and the agriculture, primarily in regards of the phosphorus that is present in the wastewater streams, but without the risk of negative health and environmental effects in both a long- and short-term perspective.

In 2018 the Swedish Ministry of Environment decided to appoint an investigation on how to formulate a law proposal regarding a ban on the spreading of sewage sludge in combination with requirements of phosphorus extraction and return of nutrition to the agriculture (Dir. 2018:67). Two years later this resulted in the final report Sustainable Sludge Management which gives suggestions based on two different scenarios on how a ban on the spreading of sewage sludge should be formulated together with requirements of returning 60 % of the phosphorus content in the sludge to the agriculture (SOU 2020:3). The law proposals in the report would affect the management of two thirds of the 200 000 tons of dry solid (DS) sludge that is produced yearly in Sweden and in the analysis conducted by the author two different technological approaches were evaluated in both of which sludge drying is a key step in the technology chain of events (SOU 2020:3).

Solar energy is one of the most scalable renewable energy sources there is and has been identified as a key source for the rapid energy transition that will take place over the year to come (Gielen et al., 2019). Solar thermal energy can play a major role in the energy transition since heat is the largest end-use and accounts for approximately half of the world's energy consumption (IEA, 2020). Since wastewater sludge is produced in large amounts wherever humans live, the use of solar thermal energy in the sludge drying process could help to minimize the climate strain of WWTPs while at the same time creating a valuable and disinfected dried sludge with a high energy value to be used as a biofuel or biofertilizer if allowed.

1.2 Aim

The aim of this report is to investigate how the sludge drying process in WWTPs can be conducted in a more sustainable way using solar thermal energy and to evaluate how the technology from Absolicon solar collector AB could be implemented in existing drying technologies and treatment plants. The thesis should also cover how feasible the implementation is compared to other technologies and discuss the benefits and problems of implementation. The thesis project will be designed as a caste study for the largest WWTP in Härnösand, the Kattastrand WWTP, which will be used as a key reference in the investigation of how solar thermal energy could be used in the sludge drying process. The goals are (1) to present an overview of current and future sludge management legislation and sludge drying technologies in Sweden and internationally, (2) to suggest potential solutions for using solar thermal energy in the sludge drying process and (3) to evaluate the feasibility of the potential solutions and give suggestions on the integration at Kattastrand WWTP.

1.2.1 Specific objectives

The specific objectives of this study are the following:

- Review current wastewater legislation and evaluate benefits and challenges related to sludge drying.
- Review existing technologies used for sludge drying today and evaluate if solar thermal energy could be integrated in pre-existing solutions.
- Review and evaluate how suitable the technology is for the purpose of drying sludge.
- Describe how sludge is used and disposed of in Sweden and give an overview of the current and future sludge management legislation.
- Review of the current sludge management at Kattastrand WWTP and give suggestions on how future management with solar thermal sludge drying could be implemented.

- Cost-benefit analysis (CBA) to evaluate the viability of the implementation compared to other alternatives together with a sensitivity analysis.

1.3 Research questions

1) How is sludge from wastewater treatment plants handled today in general and at Kattastrand treatment plant in Härnösand?

2) What technologies are used for sludge drying and how could solar thermal energy be implemented or used in the sludge drying process?

3) How viable is the implementation of the solution?

1.4 Delimitations

The thesis will primarily look at Swedish legislation and common technologies that could be utilized in Sweden, but also give a brief overview of international trends in sludge legislation and management. There are various technologies for sludge drying and this paper will only focus on those who use thermal energy as energy source due to the aim to evaluate integration with solar thermal energy. More specifically solar thermal energy from parabolic trough concentrating solar collectors and with specific technical specifications from Absolicon Solar Collector AB. Other solar technologies will not be evaluated, the results may however be applied to other technologies if they have similar technical specifications and operating temperatures. The case study will be evaluating the specific WWTP Kattastrand which is run by HEMAB in Härnösand and will use site specific data in the evaluation. Further delimitations of the thesis are that only CO_2 emissions related to the management and operation will be investigated without the emissions related to the production of equipment or full life cycle. Further simplifications, assumptions and delimitations related to the methodology will be described in the methodology chapter of the thesis.

2
Theory

In this chapter the qualitative data from the literature study will be presented which includes a broad description of sludge, solar thermal systems, Swedish legislation of sludge management and what technologies that are available for sludge drying today. Besides from this the model for economic feasibility that will be used in the study will be explained.

2.1 Wastewater sludge

Municipal wastewater is comprised of sanitary sewage, industrial wastewater, infiltration and stormwater runoff, depending on how the municipal sewage system is designed, and can have a large variation in chemical composition and characteristics (Liu & Lipták, 2000). There are various forms of wastewater treatment applications and processes available but common for them is that at the end of treatment the fractions that the wastewater ends up in is treated water that often is released to a nearby recipient and wastewater sludge. Wastewater sludge can have different characteristics and consistency and a certain terminology has been developed to distinguish these different types of sludge. Sludge from the primary and secondary clarifier is called primary sludge and bio sludge. Primary sludge consists of the solids that sinks to the bottom during pre-sedimentation, i.e., the last step of the mechanical treatment process which often is called primary treatment. When using precipitating chemicals, the term chemical sludge is used. Mixtures of these types of sludge are called mixed sludge (Svenskt Vatten AB, 2010).

There are over 400 major WWTPs in Sweden, and about 50 of them are licensed to receive wastewater with pollution amounts corresponding to at least 50 000 population equivalents (pe) (SOU 2020:3). On average 80 kg of dewatered sludge is produced per person every year, with a DS of around 25 %, this amounts to around 200 000 tons of dry solid sludge that is annually produced in Sweden alone (SOU 2020:3). The chart in *figure 1* shows the amount and proportion of large (>2000 pe connections) WWTPs in Sweden sorted after number of connections.

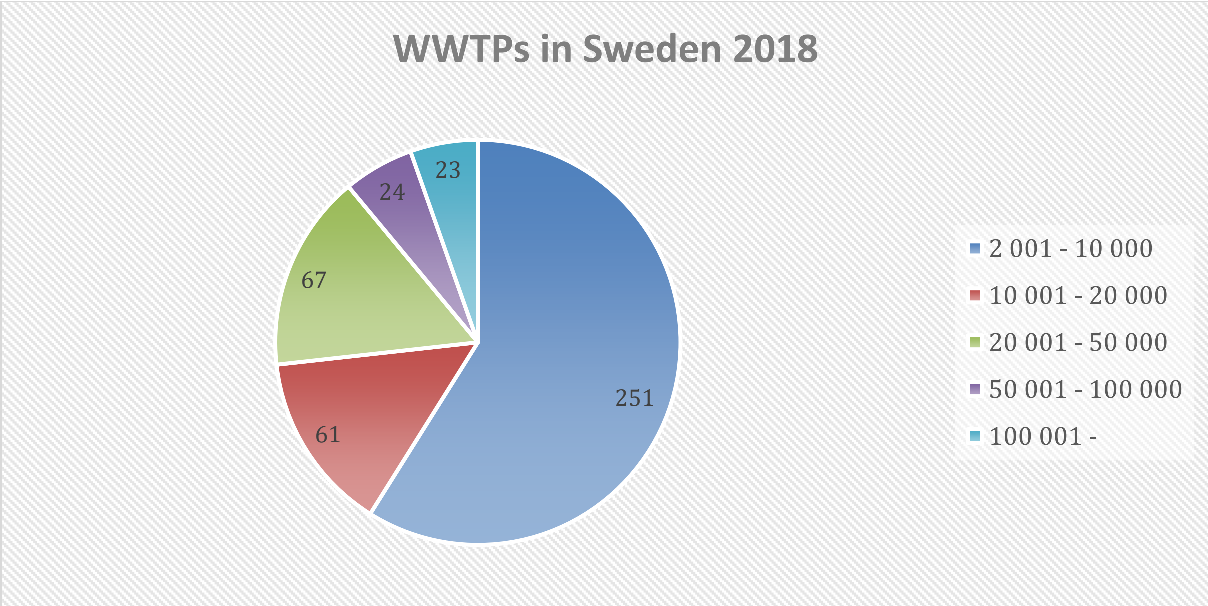

Figure 1. Number of WWTPs in Sweden sorted after connected population equivalents (SCB, 2018c).

In addition to this there are many small treatment plants, approximately 1300 treatment plants with connections between 1000 - 2000 pe, and in an approximation from 2006 it is stated that there exist around 3000 treatment plants with connections between 25 - 2000 pe (Rivera, 2006). The total amount have probably deceased since then because of the trend to decommission smaller facilities for connection to larger central wastewater treatment plants (SOU 2020:3).

The composition of the sludge varies depending on what type of wastewater that the treatment plant receives and in urban areas that have a combined sewage system the wastewater is diluted with stormwater runoff which could have high concentrations of heavy metals and other pollutant that is unwanted in the sludge depending on the end use. The large WWTPs are obliged to send samples of sludge for analysis on a regular basis and the contamination levels are reported by the county administrative boards in Sweden. *Table 1* shows some of the constituents of municipal wastewater sludge for different sized treatment plants in 2018.

Table 1. Concentrations of phosphorus, nitrogen, metals and organic indicator substances in sludge from municipal wastewater treatment plants in 2018. Weighted means in mg/kg dry substance (The Swedish EPA, 2018).

	Mean value [mg/kg] DS		
	Dimensioned population equivalents		
	- 19 999	20 000 - 99 999	100 000 -
Phosphorus	18 270	25 288	31 617
Nitrogen	36 552	44 243	51 950
Cadmium	0,7	0,8	0,7
Chromium	17,6	26,5	21,5
Copper	270	323,9	374,6
Quicksilver	0,4	0,4	0,5
Nickel	11,8	16	19,8
Lead	13,7	16,7	17
Zinc	486,3	585,4	587,3

Nonylphenol	2,6	3,5	5,8
PAH	0,34	0,48	0,88

Except for plant nutrients in the form of phosphorus and nitrogen the wastewater sludge also contains contaminants in terms of heavy metals, polycyclic aromatic hydrocarbons and toxic compounds such as nonylphenol which is an endocrine disrupter capable of interfering with the hormonal system (Soares, Guieysse, Jefferson, Cartmell, & Lester, 2008). Many of the toxic compounds found in the wastewater sludge has however been seen a significant reduction in concentrations the last 20 years (The Swedish EPA, 2018). In addition to these contaminants there are also microplastics, drug residues and pathogens that could face a risk to human health, the effects of these are not fully known as well as combination effects of multiple contaminants (SOU 2020:3).

2.1.1 Sludge legislation and limit values

The legal definition for wastewater sludge that the Swedish EPA implemented in Swedish law is *Sludge from sewage treatment plants, multi-chamber wells or similar devices that treat wastewater from households or urban areas, or from others treatment plants that treat wastewater with similar composition* (SNFS 1994:2). This is further discussed in SOU 2020:3 where it is highlighted that there are other solutions than multi-chamber wells that separate sludge and that the word sludge separators would be more appropriate and modern to use. The final proposal for a definition in the Swedish governments official investigation is *the sewage fractions to be covered by the new regulation is sewage sludge, other sewage fractions that occur during the treatment of wastewater and collected toilet water, urine, and feces. Also, sludge from treatment plants that treat wastewater with similar composition as wastewater from households and urban areas shall be included.* This means that sludge from the food industry may be covered (SOU 2020:3).

Between 1974 and 1993, the use of wastewater sludge was regulated by general guidelines and recommendations from the Swedish EPA. In 1990, the Swedish government formulated the goal that sludge must be able to be used continuously in agriculture without risks to the environment and health and that the disposal of sludge in landfills in the long run should end (Prop. 1989/90:150). Regulations on how and when wastewater sludge can be used in agriculture as well as limit values for heavy metal concentrations in the ground for when wastewater sludge can be used in agriculture was regulated 1993 but has since then been revised with gradual reductions in 1998 and 2000 (SFS. 1985:840; SNFS 1998:2; SOU 2020:3). Limit values for the concentrations of metals allowed in wastewater sludge that is intended to be used in agriculture is found in the regulation of chemical products (SFS 1998:944). In 1990, the Swedish EPA was commissioned, in consultation with the Swedish Board of Agriculture, the National Food Administration and the Swedish Chemicals Agency, to “prepare proposals for programs for the phasing out of certain environmentally hazardous organic substances and to action programs regarding sludge from municipal wastewater treatment plants”. The purpose of the assignment was that authorities and municipalities would implement measures so that by 1995, a sludge would be obtained which was safe to spread even in a long-term perspective. This commission resulted in the regulation from the Swedish EPA of how sludge would be allowed to be used in agriculture (SNFS 1994:2; SNFS 1998:2). In 1994 the

Swedish government signed the European Economic Area (EEA) agreement which brought up to date the 1986 European Community (EC) directive, 86/278/EEG, on sewage sludge. The Directive requires Member States to prohibit use of sludge if the contamination level of one or more heavy metal in the soil exceed established limit values. Member States shall regulate the use of sludge so that the enrichment of heavy metals in the earth does not lead to these limit values being exceeded. This shall be achieved by either:

- regulating the maximum amount of sludge that is annually allowed to be spread per unit area of land regarding the maximum heavy metal concentrations which are set, or by
- ensuring that the limit values for the amount of metals added to the land per unit area and time is compiled with.

The Swedish EPA was commissioned to draw up regulations to replace the current general guidelines (SOU 2020:3). This lead to the creation of the Sludge Agreement between the Swedish EPA, Swedish Water and the Swedish Federation of Farmers with the purpose of stimulating the use of quality-assured sewage sludge as a fertilizer and soil improver (SOU 2020:3). This was of great importance for the continuous work on improved upstream quality of wastewater and sewage sludge together with the development of the Revaq certification system that started 2008 and today has 42 connected treatment plants that also has played an important role in the upstream improvement work (SOU 2020:3). In *table 2* the current Swedish and European guideline values for concentrations of pollutants allowed in wastewater sludge together with the suggested values by the Swedish EPA 2013 for wastewater sludge that is intended to be used in agriculture is presented.

Table 2. Limit values for metal concentrations in wastewater sludge intended to be used in agriculture for EU, Sweden and the suggested values by the Swedish EPA 2013 [mg/kg DS] (SFS 1998:944; SOU 2020:3; The Swedish EPA, 2013).

Substance	86/278/EEC	SFS 1998:944	The Swedish EPA 2013		
			2015	2023	2030
Cadmium	20 - 40	2	1	0,9	0,8
Copper	1000 - 1750	600	600	550	475
Nickel	300 - 400	50	40	35	30
Lead	750 - 1200	100	35	30	25
Zinc	2500 - 4000	800	800	750	700
Quicksilver	16 - 25	2,5	1	0,8	0,6
Chromium	-	100	60	45	35
Silver	-	-	5	4	3
BDE-209	-	-	0,7	0,5	0,5
Dioxin	-	-	20	15	10
Chlorinated paraffins	-	-	4	3	2
PCB	-	-	0,06	0,05	0,04
PFOS	-	-	0,07	0,05	0,02

In 2013 the Swedish EPA presented a report to the Swedish government as a result of the government assignment to evaluate phosphorus recycling with proposals for continued upstream work. The report contains limit values for eight selected metals and five organic parameters as well as proposals for hygiene treatment of the sludge which is seen in table 2 above (The Swedish EPA, 2013). The proposal in 2013 entailed tightening the limit value for chromium and the introduction of a limit value for silver and a gradual reduction of the limit values over time, a model that is also used within Revaq (The Swedish EPA, 2013). Similarly the suggestion for limit values on the organic parameters as well as hygiene treatment of the sludge is also currently used in the Revaq system (SOU 2020:3).

The latest development in the sludge legislation in Sweden is the state's public inquiry on sustainable sludge management that in 2018 commissioned an investigation on evaluating a ban on the spread of sewage sludge on arable land. It was stated that spread of sewage sludge should be phased out and replaced by technologies where phosphorus is recycled without spreading substances that are harmful to the environment and health. A special investigator was therefore assigned to investigate how a ban on the spread of wastewater sludge combined with requirement for the extraction of phosphorus from sewage should be formulated. The proposals were required not to prevent the extraction of biogas from sewage sludge through digestion. The investigator was also commissioned to report on the technical development that has taken place with regard to the treatment of sewage sludge and investigate whether there is a need for an establishment or investment support for the technical solutions required to recover phosphorus from sewage sludge. As well as propose how continued upstream work to reduce emissions near the source can be ensured after a ban on the spread of sewage sludge has been introduced.

The report on sustainable sludge management was presented in early 2020 to the ministry of environment and based on different scenarios concerning a phase-out of future sludge spreading, the Inquiry formulated two options for future regulation. The Inquiry's proposed ban option (1) relates to a complete end to sludge spreading with very few exceptions. This has, however, been deemed to be a less realistic alternative according to the inquiry, given the absence of evidence regarding negative effects on health and the environment and compatibility with the EU regulatory framework (SOU 2020:3). It is also stated that this option would further steer towards the development of large-scale technical solutions, principally the incineration of sewage sludge with subsequent phosphorus extraction from the ashes. And if incineration is the resulted end use, incitements for biogas production may be reduced (SOU 2020:3). The second ban option (2) takes other factors into account, for example the possibility of applying the ecocycle principle to phosphorus, a number of other plant nutrients and the carbon content of the sludge. Possible risks to health and the environment are managed in accordance with the precautionary principle through recurrent checkpoints, with broadened and tightened requirements for quality and sanitation when spreading sludge on productive arable land (SOU 2020:3).

2.1.2 Sludge management

In Sweden, the municipalities are legally responsible for collection, recycling and disposal of household waste in which wastewater sludge is included. They are also in most cases the owners of the WWTPs which produce the wastewater sludge. The municipality also decide who is in charge of areas of activity and regulate the water and sewage tariffs that finance the WWTPs (SFS 2006:412). However private contractors can be hired when there is a need for it.

As mentioned before there are various steps in the WWTP where sludge is produced depending on what treatment processes that the facility has adopted. Before the sludge is transported from the treatment plant for storage or towards its end use there is usually some sort of treatment at the plant depending on the design and size or the treatment plant. For example, at Ryaverket in Gothenburg, one of the largest treatment plants in Sweden the treatment steps for the sludge are the following:

- Mesh fabric and belt gravity thickener with addition of polymers increasing DS from 2 to 4 %.
- Biogas production where the sludge is digested mesophilically in an oxygen-free environment.
- Dewatering in screw presses to a DS of around 70 %.
- Long-term storage of sludge for spreading on arable land to cope hygiene requirements, shorter storage of sludge to be used in other applications (Ryaverket, n.d.).

Undigested sludge has a low content of DS and consists of easily degradable organic material. It is difficult to store, produces methane and other gases, generates a lot of odor and contains pathogens (SOU 2020:3). The sludge is not yet suitable for handling and spreading and it needs to be stabilized and dewatered. In the most cases the sludge is digested or stabilized, either at the treatment plant in question or at a major treatment plant in the region. Often smaller treatment plants send their sludge to larger facilities where they can digest larger amounts of sludge for biogas production. Such treated sludge contains a number of resources in the form of plant nutrients and soil substances, but also unwanted and sometimes harmful substances and pathogens (SOU 2020:3). Further treatment steps depending on the WWTP design could be liming, drying, urea treatment, composting, thermal treatment or long term storage (The Swedish EPA, 2013). When the sludge is transported between treatment plants and sludge storage the sludge is normally picked up at the treatment plant by truck, where the treatment plant stands for the cost through a fixed price per ton or cubic meter. Storage is usually sorted in batches often with breakdown by month of production the sludge (SOU 2020:3).

The end use of the just over 200 000 tons of sludge that is annually produced by the large WWTPs in Sweden has varied over time and varies geographically between the different regions. In total the largest end use category in 2018 was direct spreading on arable land, after the sludge has been treated or stored to meet the hygiene requirements (The Swedish EPA, 2018). This category has increased from 26 to 39 % between 2008 and 2018 (The Swedish EPA, 2018). The overall spread and use of sewage sludge for various purposes at national level are reported every two years, the latest data is from 2018. Distribution routes 2018 are summarized in *figure 2*.

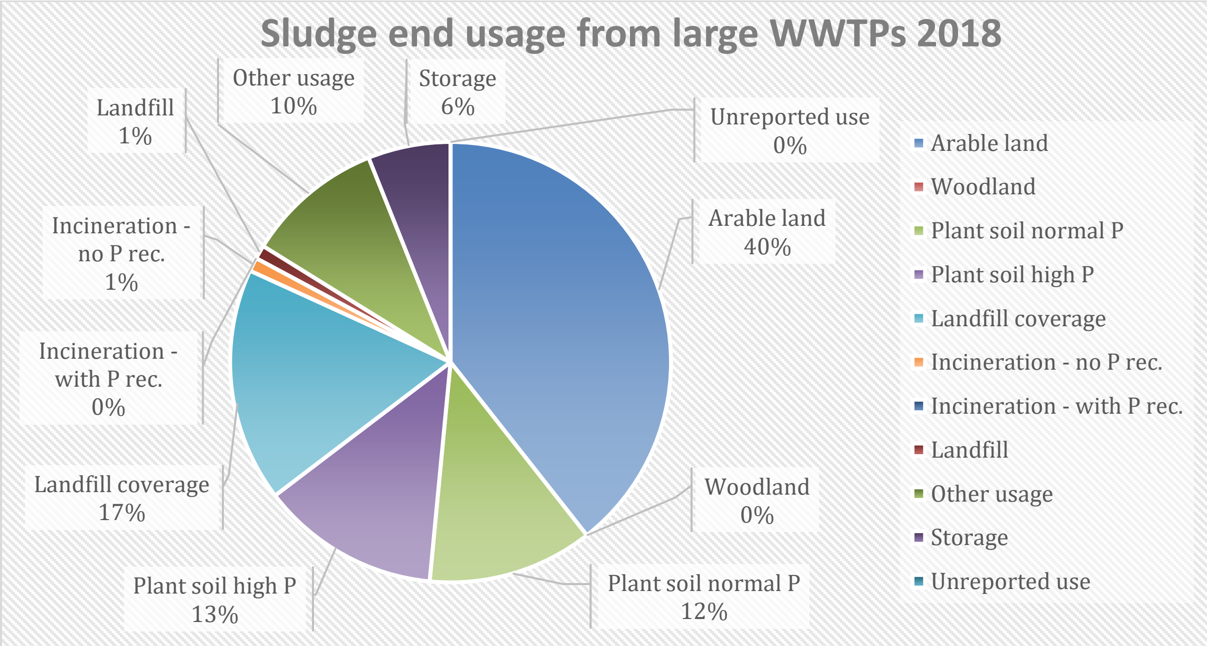

Figure 2. Sludge end usage from large WWTPs 2018 (SCB, 2018b).

The end use varies depending on the quality of the sludge and if the sludge is going to be spread on arable land there are established reference values of what contamination levels that is allowed but also there needs to be agriculture land reasonably close to the WWTP.

Table 3. Wastewater sludge production in ton DS and end use in percent of production per county and for the whole of Sweden (SCB, 2018a)

	Production	End use [%]						
County	[Ton DS]	Arable land	Wood-land	Plant soil normal P	Plant soil high P	Landfill coverage	Incineration - no P rec.	Landfill
Sweden	211 604	39	0	12	13	17	1	1
Stockholm	41 448	38	0	0	42	6	0	0
Uppsala	6450	40	0	10	5	26	4	0
Södermanland	6091	73	0	1	5	26	0	0
Östergötland	9550	47	0	8	3	24	0	8
Jönköping	7535	48	0	21	0	3	0	8
Kronoberg	4223	62	0	0	0	33	0	0
Kalmar	5456	47	0	11	5	17	0	0
Gotland	1470	15	0	0	0	0	0	0
Blekinge	4327	55	0	10	0	3	0	0
Skåne	29 676	50	0	31	0	9	3	0
Halland	8302	64	0	2	14	6	0	0
VästraGötaland	33 359	43	0	3	20	18	3	1
Värmland	6729	35	0	16	4	33	0	1
Örebro	7086	57	0	16	0	28	0	0
Västmanland	5784	46	0	17	0	10	11	0
Dalarna	9284	0	0	34	7	17	3	0
Gävleborg	5759	0	0	10	0	78	0	0
Västernorrland	4287	0	0	64	0	13	0	0
Jämtland	1968	0	0	0	0	50	0	0

Västerbotten	6458	1	0	2	8	59	0	0
Norrbotten	6363	0	0	31	0	1	0	12

Sludge producers can maintain direct contact with operators that could use the sludge or manage their sludge with help of contractors. The recurring public procurements for sludge disposal are thus of great importance for the sludge management and has a large impact on how the sludge is used. An important aspect that affects end use is also of what quality the sludge has in terms on contamination and if the sludge is certified in the optional certification system Revaq (SOU 2020:3). The end user usually does not pay to receive the sludge.

The most common sludge treatment processes for WWTPs with more than 5000 - 10000 connected pe is thickening with a gravity thickener or a mechanical thickener, then the sludge is stabilized through digestion and thereafter dewatered, usually with a centrifuge (Svenskt Vatten AB, 2013). This reduces the volume of the sludge and gives a DS of about 25 %, smaller treatment plants can have different more simple methods such as reed beds (Svenskt Vatten AB, 2013). If the sludge is to be incinerated, it first has to be dried to achieve a better calorific value.

In the Sludge strategy for Stockholm Water and Waste from 2018 the municipality evaluated different sludge management options for the city in regards of the decision criterions of climate impact, resource management, reliability, economy, the national environmental goals as well as that the management needs to be compliant with current legislation. The different options were ranked depending on the score of each underlying criterion and a list of the best options were presented in the results of the management strategy. None of the options that was evaluated got top score in each criterion but the best option that was evaluated was direct spread on arable land. The second best was drying the sludge and afterwards spreading it on arable land, this option reduced transports, increased hygiene and made storage easier. The option required a large investment in sludge drying facility as well as space for it to be built and would require energy costs for operating but it was discussed that such an investment might be useful for the future in case the sludge was not allowed to be used in agriculture (Stockholm Vatten och Avfall, 2018).

2.1.3 Sludge drying

The reasons for drying sludge are plenty but varies a bit depending on what the end use of the sludge is. When drying sludge, the volume and weight of it is reduced, this is a positive aspect when transporting the sludge as it is possible to reduce the number of truckloads and thereby costs and emissions related to these. Other reasons is for disinfection of the sludge, thermal drying is one of the recommended methods for hygienization of sludge (The Swedish EPA, 2013). If the sludge is to be incinerated sludge drying is necessary to achieve a higher calorific value of the sludge which is needed for thermal utilization of the sludge (Flaga, 2007). Completely dried sludge has a calorific value that ranges between 12 - 14 MJ/kg of DS which is similar to that of peat (Flaga, 2007). It is recommended that sludge is dried to a minimum of 40 % DS but preferably higher, up to 90 %, DS before incineration to achieve better properties as fuel (Flaga, 2007).

Sludge drying is a technology that has been established for many years and is considered well mastered. There are several types of dryers developed using different types of heat carriers and energy sources, but this section will describe different technologies that use thermal energy for drying. A principal advantage of drying is that the amount of sludge decreases since water is evaporated. After digestion and dewatering, the sludge weigh about 70 – 100 kg per pe and year. After drying, this amount decreases to 20 – 25 kg per pe and year (Svenskt Vatten AB, 2013). The volume of sludge does not decrease equally much as dried sludge has a bulk density of less than 1 ton/m^3 and pelletized sludge of about 0.6 tons / m^3 (Svenskt Vatten AB, 2013).

Drying is a process that requires a lot of energy, theoretically 0.7 kWh per kg of stripped water and with the annual production of 20 kg DS per pe given a 30 % DS, this theoretically corresponds to 33 kWh per connected person and year (Svenskt Vatten AB, 2013). However in practice there are estimates of an annual energy consumption of at least 40 – 60 kWh per pe (Svenskt Vatten AB, 2013). To evaluate what energy demand to use in calculations *table 4* is compiled with different values that has been used in various papers and studies.

Table 4. Values for energy demand in sludge drying from various references.

Reference	Energy demand used in the reference	Comparison
(Svenskt Vatten AB, 2013)	0,7 kWh per kg of stripped water, corresponds to 33 kWh per connected pe and year with a 30 % DS assumed	0,7 kWh per kg of stripped water
(Svanström, Heimersson, & Harder, 2016)	Drying from 25 to 90 % DS consumes 0,125 MWh/ton DS sludge assuming 75 % energy recycling	0,82 kWh per kg of stripped water
(Wittgren, Von Bahr, Kärrman, Lundin, & Rodhe, 2017)	Drying from 25 to 95 % DS requires 2 MJ/kg dewatered sludge	0,79 kWh per kg of stripped water
(Baresel, Lüdtke, Levlin, Fortkamp, & Ekengren, 2014)	900 – 1500 kWh per ton stripped water	0,9 – 1,5 kWh per kg of stripped water
(Baresel, Lüdtke, Berg, Åfeldt, & Aronsson, 2016)	Drying from 25 to 90 % DS consumes 0,86 – 1,2 kWh/l of stripped water	0,86 – 1,2 kWh per kg of stripped water

Biogas from the wastewater sludge can cover this energy demand but other energy sources are also possible and with the addition of heat exchangers, a well optimized system can reduce the total energy demand (Svenskt Vatten AB, 2013). Thermal drying is also one of the recommended treatment methods to achieve the recommended hygiene standard by the Swedish EPA where they recommend temperatures of at least 80°C with at least 10 minutes of exposure and a dry solid of at least 90 % (The Swedish EPA, 2013). Another recommended hygiene treatment method is thermal treatment where they recommend exposure time and temperatures that should follow equation 1 below (The Swedish EPA, 2013).

$$t = 10^{(-0.0963 \times T + 6.3)} \tag{1}$$

t = exposure time
T = temperature in degrees Celsius with a minimum of 52°C

An important physical aspect of sludge drying is what is called the sticky phase of the sludge that occur after it has been dewatered and before reaching a higher percentage of DS. The sticky phase is when the sludge has a DS content of around 25 - 40 % (Peeters, Dewil, & Smets, 2014). Negative effects that can occur is higher torque requirements of centrifuges and sludge paddle dryers, sludge build up on the dryer surfaces and potential equipment damages related to these issues (Peeters et al., 2014). A regular solution to handle the problem is to mix the sludge with dried sludge before drying it or having a low enough DS for it not to have entered the sticky phase (Baresel et al., 2016; Peeters et al., 2014). The physical properties of the different phases are shown in *figure 3*.

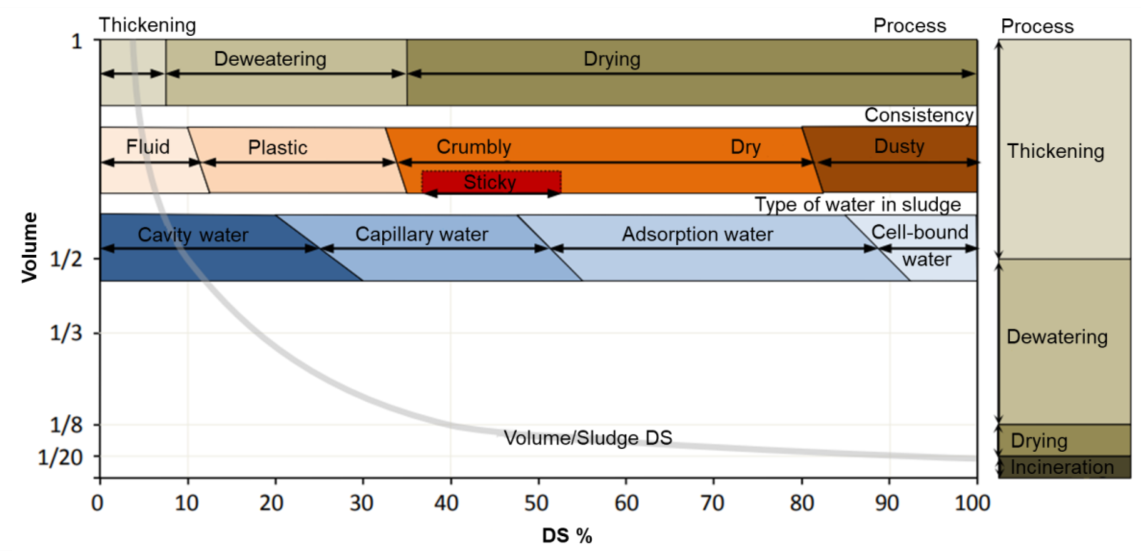

Figure 3. Overview of characteristics and physical properties of wastewater sludge during the dewatering and drying process (Baresel et al., 2014).

As seen in the figure the sticky phase is just one of the multiple phases during sludge drying and the largest volume change happens during the dewatering although a larger amount of water dissipates during the drying.

Below a short description of some different technologies based on thermal energy that are used in sludge drying are presented.

Belt dryer uses convection as drying method where hot air is circulated within the system to dry the sludge to the desired DS %. The heat transfer medium is water with temperatures ranging from 70 - 150°C (Huber, n.d.-b). Via a heat exchanger different energy sources can be utilized for the process, especially exhaust and waste heat from various sources (Huber, n.d.-b).

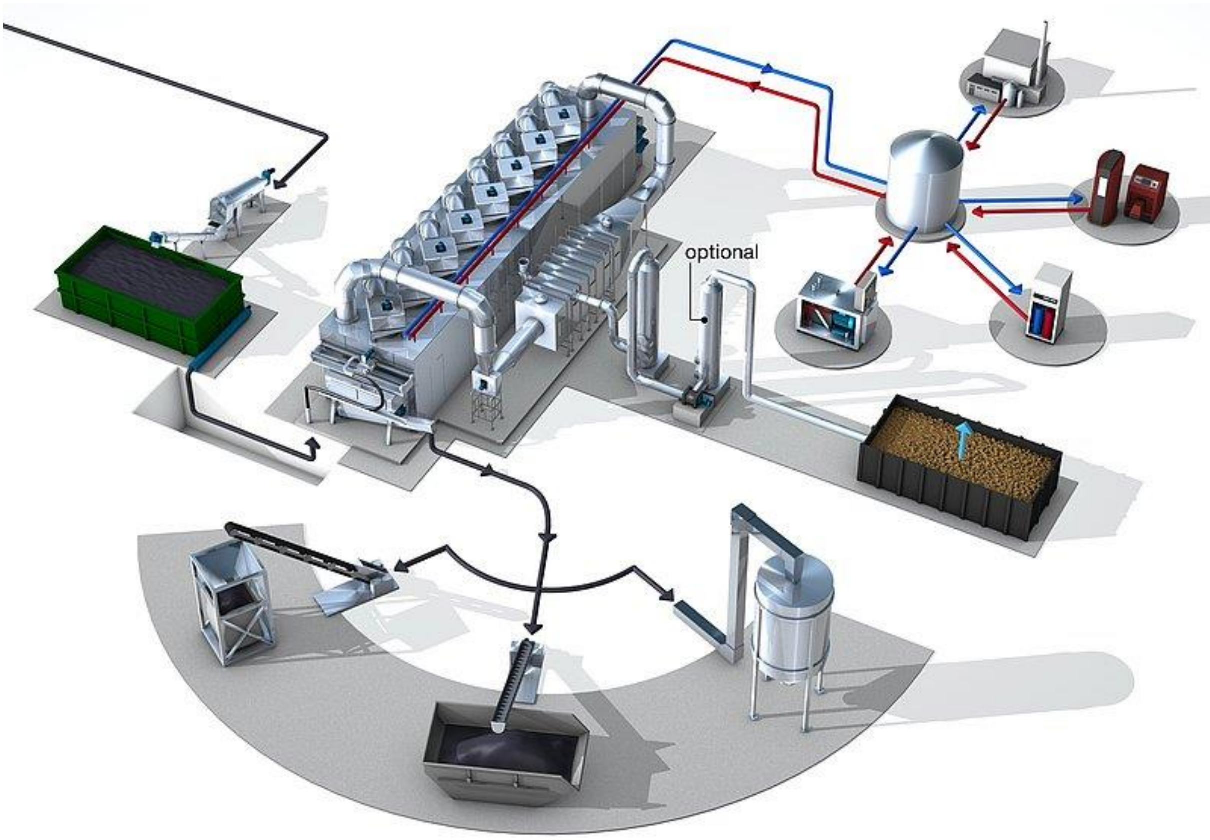

Figure 4. Conceptual model of a belt dryer application from Huber (Huber, n.d.-b).

The integration of process energy available on site is common practice. Thermal energy demand for a belt dryer from according to the supplier is between 0,8 to 0,9 kWh/kg water evaporation and the product can be dried up to 95 % DS (Huber, n.d.-b). Heat recycling from condensate water of at least 15 % is possible according to information retrieved from the supplier.

Rotary dryer utilizes conduction as the drying method and uses a rotating cylindrical drum to transfer the thermal energy from the heat carrier inside to the sludge on the heated envelope of the rotating cylinder (Berk, 2018).

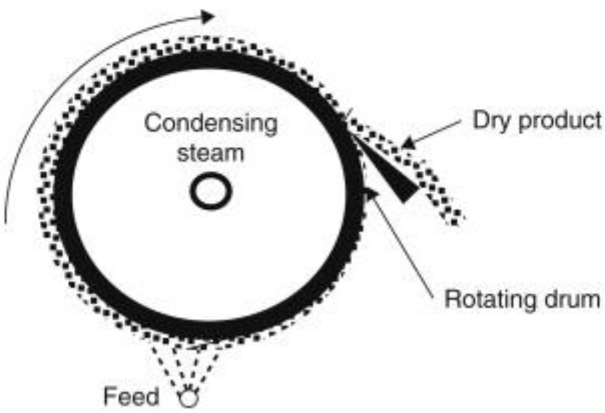

Figure 5. Conceptual model of a drum dryer (Berk, 2018).

The rotary dryers can also dry the sludge up to 95 % DS and energy demand varies with supplier but is similar to the belt dryer. The energy sources can vary and it is possible to utilize waste heat but normal operation depends on what is available at the treatment plant but and usually consists of biogas or fossil fuels (Haarslev, n.d.).

Solar dryers currently exist as a sort of greenhouse solution which can be open, closed and combined with heated floor. Huber technology is a supplier that has a solution with this type of technology and they can dry the sludge above 65 % DS and integrate with waste heat or other energy sources (Huber, n.d.-c).

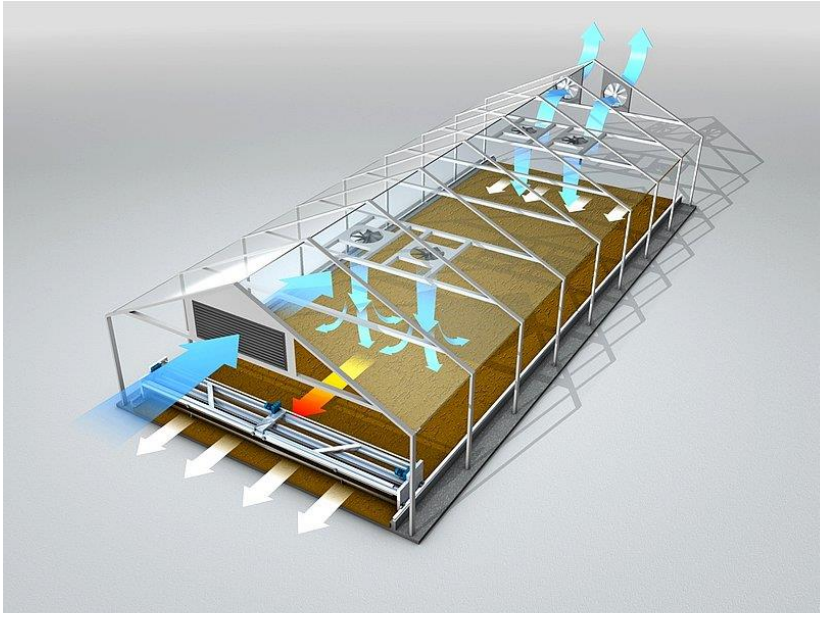

Figure 6. Conceptual model of a greenhouse solar sludge dryer (Huber, n.d.-a).

The system also works well with sub-freezing outdoor temperatures according to the supplier but to achieve hygiene requirements further treatment is required (Huber, n.d.-a).

An interest company to Absolicon has developed an evaporator that is suitable for viscous, highly fouling or sticky products. The evaporator is using a vacuum system, continuous scraping operation and falling film configurations that allows temperature and product control. The system is designed to utilize heat sources such as industrial solar heat, medium temperature waste heat or any other conventional sources but is currently un-tested on wastewater sludge (Jonatan Mossegård, personal communication).

Other promising dryers that are recently developed is a Freeze dry unit from Elajo, that freezes, melts and dries the sludge to a DS between 30-95 % depending on the end use and a superheated steam dryer from Swedish Exergy that utilizes pressurized steam to dry the sludge (Elajo, n.d.; Swedish Exergy, n.d.).

2.1.4 International trends in sludge management and legislation

Of the Scandinavian countries Sweden is the largest producer of sludge, second comes Finland with 160 000 ton DS, then Denmark with 132 000 and finally Norway with 118 000 ton DS annual sludge production (SOU 2020:3). The largest end use in all the countries is direct spread on arable land. The management of wastewater sludge is somewhat similar in all the countries, in Norway there are in general a more decentralized system with more smaller facilities compared to its neighboring countries. All the countries have developed their own legislation with more strict guideline values and quality assurance than compared with the EU legislation. Denmark is the only country that currently has goals of phosphorus recycling and has since long had mono-incineration of wastewater sludge in Copenhagen (SOU 2020:3). In Norway, the focus on phosphorus is not the key take away but instead the use of sludge in agriculture is primarily to enhance the ground with soil-forming substances. They have implemented strict requirements for pathogen control and there can be no viable parasite eggs in the hygienized sludge, sludge drying is considered a valid hygiene treatment method to ensure quality of the sludge (SOU 2020:3).

In Europe there are large variations in both sludge management and legislation between countries. In Switzerland wastewater sludge spread on arable land has been prohibited since 2006 and two thirds of the produced sludge is mono-incinerated and by 2026 75 % of the phosphorus in the ashes shall be recycled (SOU 2020:3). Germany is one of the largest producers of wastewater sludge in Europe and only a small fraction of it is used in agriculture. The country has a long history of burning coal and has been using these powerplants to co-burn the sludge (SOU 2020:3). Recent development has been an adaptation to be able to cope with future requirements of phosphorus recycling and by 12 - 15 years the large treatment plants are obliged to recycle 80 % of the phosphorus from mono-incinerated sludge ashes (SOU 2020:3). In Great Britain it is considered a best practice environmental option to use sludge in agriculture and more than 75 % of the produced sludge is being spread on arable land (SOU 2020:3). Current legislation is however being reviewed but the regulations future design is difficult to assess due to Brexit (SOU 2020:3).

2.1.5 Climate impact of wastewater sludge

In addition to the climate impact that the sludge treatment's direct and indirect energy use entails, the sludge treatment can lead to direct emissions of greenhouse gases. It is mainly from sludge tanks after digestion and from storages with dewatered sludge that the methane and nitrous oxide is leaked and there has been reports of emissions that could be up to 2 - 3 % of the produced biogas (Svenskt Vatten AB, 2013). The biogas production does however all in all reduce the total climate strain due to the replacements of fossil fuels (Svenskt Vatten AB, 2013). Sludge spreading and storage can also lead to the emission of nitrogen oxides but the scope of these emissions are poorly understood (Svenskt Vatten AB, 2013). Transports are also a factor that leads to greenhouse gas emissions but this is a local factor that varies depending on how far the sludge needs to be transported, a dried sludge reduces these emissions substantially (Svenskt Vatten AB, 2013).

2.2 Solar thermal energy

The globally installed solar thermal capacity has between the years of 2000 and 2017 grown by a factor of 7,6 and by 2017 installed solar collectors amounted to about 675 million m^2 (Weiss, Spörk-Dür, & Mauthner, 2017). The corresponding energy yield that this installed capacity gives annually amounted to 388 TWh by 2017 which equals almost 42 million tons of oil (Weiss et al., 2017). There various types of solar collectors developed for different applications that are effective in various temperature ranges and *figure 7* gives an illustration of what is available on the market.

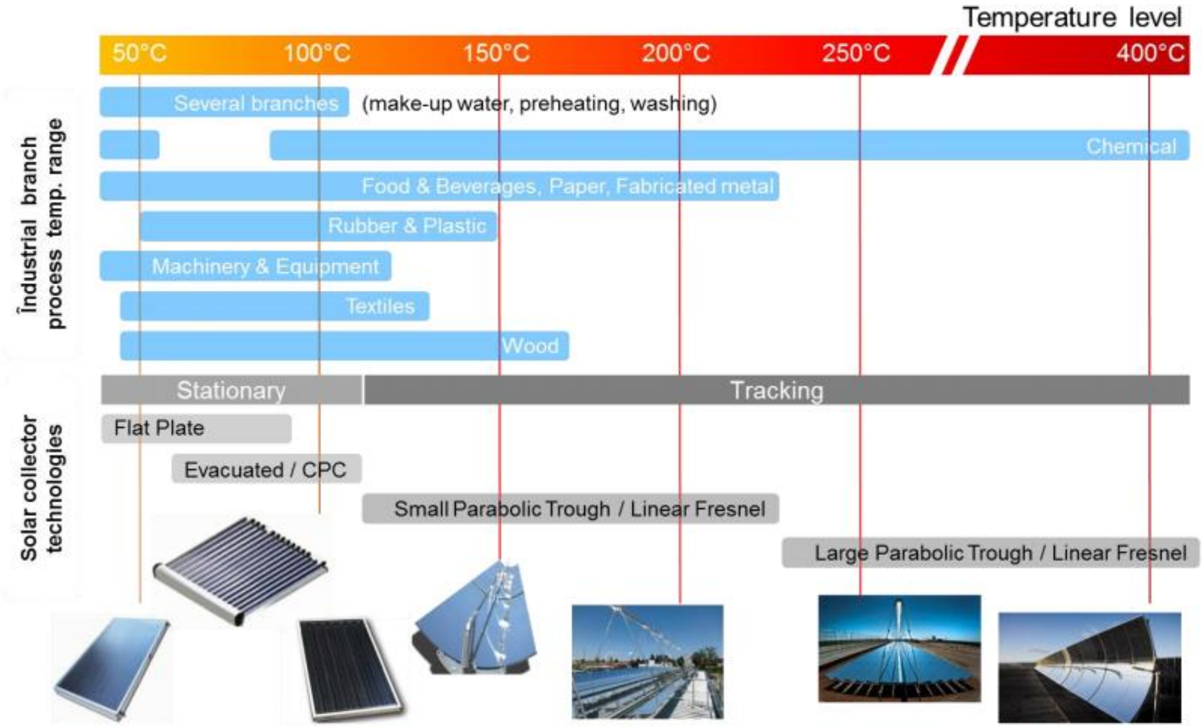

Figure 7. Solar collectors sorted after tracking capabilities and working temperature range (Giovannetti et al., 2016).

Another key factor for a solar thermal collector is whether or not it can track the sun during the day, this gives the advantage of a significantly higher energy output and an increased utilization of the solar energy (Giovannetti et al., 2016).

The energy output from a solar thermal collector is limited by how much sunlight that hits the earth surface. The radiation that hits the earth's atmosphere is of nearly fixed intensity, it is called the solar constant and amounts to 1367 W/m^2, this solar radiation is however reduced before it hits the earth's surface (Duffie, Beckman, & Blair, 2020). The reduction is due to scattering and absorption of the molecules in the air, that is why energy output will depend on weather conditions. The solar energy that hits the surface of the earth is referred to as global horizontal irradiance and consists of direct normal irradiance (DNI) and diffuse irradiance of the sun, which varies around the globe (Duffie et al., 2020). The DNI has a large impact on energy output of a solar collector, as well as technical specifications such as optical efficiency and heat loss coefficients.

2.2.1 Parabolic trough collectors

Absolicon Solar Collector AB has developed the T160 collector which is a parabolic trough collector (PTC) with one-axis tracking system that concentrates the sunlight over a collector area onto a receiver tube and deliver temperatures up to 160°C (Absolicon Solar Collector, n.d.-b). *Figure 8* illustrates the concept of the technology.

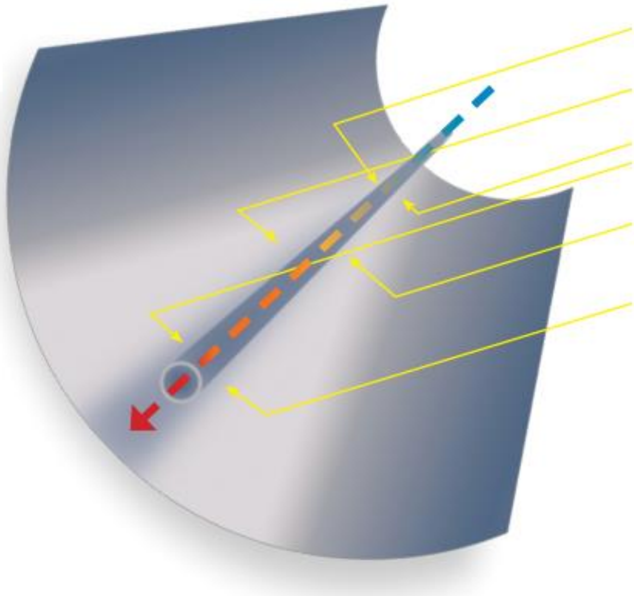

Figure 8. Principle schematic of a parabolic trough collector (Absolicon Solar Collector, n.d.-b).

The T160 collector has a working temperature between 60 – 160°C that uses water and propylene glycol as heat transfer fluid (Absolicon Solar Collector, n.d.-b). The energy output from such a collector varies depending on where the collector is installed and *figure 9* gives an illustration of how the energy output is compared to the DNI that day.

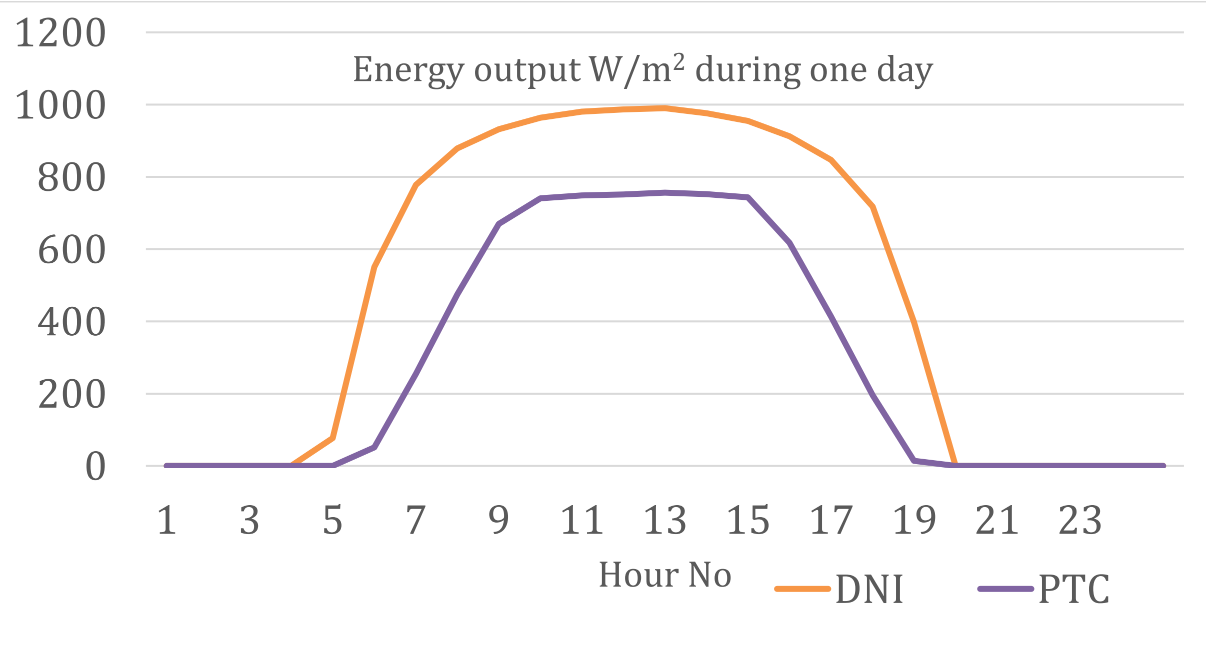

Figure 9. Energy output from a PTC collector compared to the DNI that day.

The performance seen above is specific to that installation but illustrates how much energy that could be utilized compared to what is received on the earth on a typical day. The energy production for the T160 collector in the figure amounts to 7,18 kWh/m^2 compared to the DNI that amounts to 11,9 kWh/m^2. Absolicon has created an online field simulator that can be used to get preliminary energy output data (Absolicon solar Collector, n.d.-a).

2.3 Cost-benefit analysis

Cost-benefit analysis (CBA) is an economical assessment which is used as a systematic approach for decision support and is a commonly used method for public welfare calculations and socio-economic analyses (D. W. Pearce, 2016). The CBA can be used when evaluating different investment alternatives or when potential projects should be undertaken as well as decide if the project is sound and determine which alternative is the best in relation to the zero alternative (Mishan & Quah, 2020). The analysis is conducted by estimating positive and negative consequences of alternatives i.e. costs and benefits related to the identified scenarios to provide answer of which option is the most beneficial and viable (Söderqvist et al., 2015). This is done by calculating the net present value (NPV) of the available alternatives which is the sum of benefits minus costs, and if the NPV is positive the investment alternative is socially profitable, the highest NPV is the best alternative (Mishan & Quah, 2020). NPV is expressed in monetary terms and adjusted for the time value of money which can be considered inflation, uncertainty and opportunity costs, this time value is represented by a discount rate (D. W. Pearce, 2016). The formula to compute the NPV is presented below and should be calculated for each project option in relation to the zero alternative as the discounted sum of benefits minus the costs for every year of the expected lifetime (Gallo, 2014; D. W. Pearce, 2016).

$$NPV_i = \sum_{t=0}^{T} \frac{1}{(1+r)^t} (B_{it} - C_{it}) \qquad (2)$$

NPV = Net present value for each project option (i)
B = benefits for each option (i) and every time period (t)
C = costs for each option (i) and every time period (t)
r = discount rate
T = the length of the calculation period (year)
t = time period, year

There are various variants of conducting a CBA and it is possible to include greenhouse gas emissions, health effects, social parameters and other qualitative parameters, this is often the case when conducted as a socio-economic analysis (Rosén et al., 2008). Then the effects are estimated in monetary terms and applied to the calculation of costs and benefits (Rosén et al., 2008). There are disagreements among scholars concerning what approach is most correct and therefore the structure of a CBA varies. The aim is however the same and it is to calculate changes in public welfare by determining costs and benefits for all affected by the project (Hanley & Spash, 1996; Rosén et al., 2008). The essential steps are most often the same and they include (1) define the project, (2) identify economically important impacts, (3) quantify impacts in monetary terms and (4) conduct a sensitivity analysis (Hanley & Spash, 1996). Another aspect of importance is to identify whose costs and benefits to consider in the analysis (D. Pearce, Atkinson, & Mourato, 2006). The effects of how costs and benefits are distributed amongst affected groups are recommended to be analyzed in a distributional analysis to show if certain groups are affected more by the outcome than others (Rosén et al., 2008).

The discount rate is as previously explained a time value of money and it is used to make future costs and benefits comparable with present day value (Rosén et al., 2008). The discount rate can be decided on different terms depending on what type of CBA that is conducted but it is often related to the risk-free rate with addition of a risk factor and opportunity cost to achieve a dynamic cost-effectiveness (The Swedish EPA, 2012). Values for the discount rate as recommended by ASEK which is a workgroup especially for socio-economic analysis, comprised of the Swedish Transport Administration, the Swedish EPA, Vinnova and SIKA is 4 % and the business economic real interest rate of 5 % (SIKA, 2005; Trafikverket, 2020a). ASEK 5 has however recommended a discount rate of 3,5 % considering risks and arguments for future declining rates (Trafikverket, 2020a). Other suggested discount rates are 1.4 % by Stern and furthermore Rosén that advocates examining a discount rate of 0 % in the sensitivity analysis (Rosén et al., 2008; Stern, 2007).

3
Methodology and implementation

This chapter describes and justifies the methods that have been used to answer the research questions. The study is of an explanatory nature and intends to provide system explanations for how implementation of solar thermal energy could be used in the sludge drying process both in general and specifically through the case analysis of Kattastrand WWTP. Against this background an inductive method approach has been chosen as the study is based on data collection and tries to draw explanatory conclusions. The structure of the methodology is visualized in the flowchart in *figure 10.*

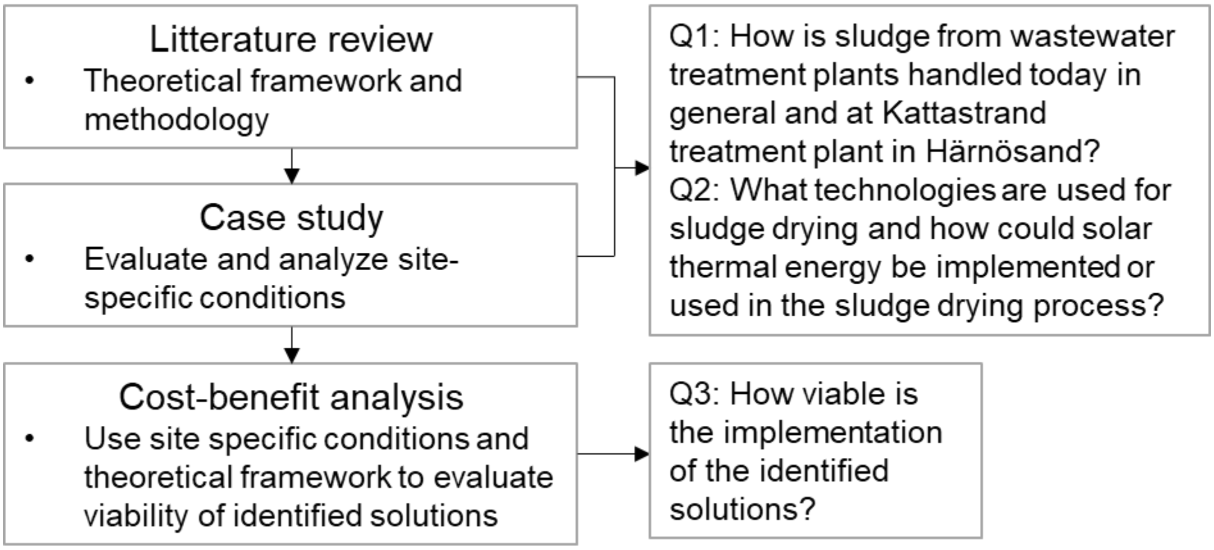

Figure 10. Illustration of methodology structure in combination with research questions.

3.1 Literature review

The study will start with a literature review where literature is read and sorted into an archive. During the course of the study new literature will be added to the archive if deemed necessary. The initial purpose of the literature study is to gain an insight into the current state of research and to gain an overview of what type of legislation there is regarding sludge management as well as what type of technologies that exist for sludge drying. The literature review will be the base of the theoretical framework and will be a continuous work when the theoretical framework is established. The theoretical framework will be used to draw conclusions of how solar thermal energy could be used in the sludge drying process.

In order to create a report of good quality, great emphasis has been placed on choices of references. This was done by basing the literature study and statistical data on reports and publications from well-established institutes, organizations and academically recognized writers as well as using published material from the latest decade and with a priority on more recent publications to get the most up to date information available. The Swedish governments public inquiry on sustainable sludge management from 2020 has been a key source for the report together with publications by the Swedish EPA in combination with statistics from the Central Bureau of Statistics.

3.2 Data collection

To get an overview of current sludge management on an aggregated level quantitative secondary data has been collected from the Central Bureau of Statistics as well as through direct contact with Kattastrand WWTP to be able to compare the case study with national and regional data. In addition to this an interview with representatives from Kattastrand and large WWTPs has been conducted to gain insights in how the treatment plants are preparing for possible future legislation.

3.2.1 Secondary data

Quantitative secondary data was collected to be able to compare the case study treatment plant with aggregated data on national and regional levels. The data consists of contamination levels as well as end use of wastewater sludge. Since contamination levels and end use can change year to year only the most recent years of data is of interest and has been analyzed. The data has been processed with the use of Excel to make calculations easier and to visualize the results in charts and diagrams.

3.2.2 Interview

An unstructured interview with a representative from Gryaab AB which is the municipal company running the Rya WWTP in Göteborg has been conducted to gain insight in how the large treatment plants are strategically planning for potential future sludge legislation. This method has been used to discuss and to get a critical picture of the newly proposed legislation and the potential use of solar thermal energy in sludge drying which could be a key process in future sludge management. The interview was recorded and transcribed to ease the forthcoming analysis of the material (Denscombe, 2014).

3.3 Case study

The thesis will be examining and evaluating how to implement solar thermal technology in sludge drying both in general but also specifically at Kattastrand wastewater treatment plant. Through direct contact with representatives from the WWTP information about processes and management is retrieved as well as data of contamination levels of the sludge. When evaluating Kattastrand WWTP site specific data will be used in the analysis and later discussed and evaluated in the sensitivity analysis.

3.4 Cost-benefit analysis

In short, a CBA can be conducted in four steps with the first step being to define the objective function, decide what alternatives are being analyzed including the zero alternative (Rosén et al., 2008). The second step is to identify the costs and benefits that are relevant for the alternative, it is possible to include social and environmental benefits here (Mishan & Quah, 2020; Rosén et al., 2008). The third step is to quantify the costs and benefits, to evaluate how to monetize the identified costs and benefits. In this step the analyst needs to decide on valuation methods but also identify if something cannot be quantified in monetary terms. The fourth step is to compute the NPV, according to formula (2) for each alternative including the zero alternative, evaluate results and identify uncertainties that are associated with the valuation methods of choice (Mishan & Quah, 2020; D. W. Pearce, 2016). The calculation is based on assumptions and estimates and a sensitivity analysis should always be conducted when using the CBA method (Gallo, 2014).

The first step of the CBA is to identify potential solutions of how solar thermal energy could be implemented in the sludge drying process for the specific WWTP and to define the reference alternative which is the current sludge management at that WWTP. This is done in chapter 4.

The second step is to identify all positive and negative consequences related to the solution scenarios that was identified and explained in chapter 5. These consequences represent costs and benefits and is identified in context to the reference alternative, they are qualitatively identified and divided into categories, assessed weather they are of importance or not and if to be used in the economic analysis. In the study by Grundestam et al. (2020) a life cycle analysis has been presented, and one of the results of that was the effect on various environmental and health categories of analyzed measures regarding the reference alternative as well as the implementation of the suggested technology chains presented by SOU2020:3. These effects are presented in different units such as for example carbon dioxide equivalents and phosphate equivalents and since many of the measures and management options for Kattastrand WWTP are similar to those in the study by Grundestam et al. (2020) it is considered valid to use the relevant values as the base of this study. The categories evaluated by Grundestam et al. (2020) are eutrophication, acidification, climate change, cadmium health effects and abiotic resource consumption (Grundestam, Johansson, Mellin, Malmaeus, & Rahmberg, 2020). In this study acidification is not included as recommended by ASEK 7, cadmium health effects are not included since deemed irrelevant as the wastewater sludge is not used in agriculture and instead of abiotic resource consumption a project economic calculation was included.

Table 5. Values for positive and negative consequences related to the reference scenario and identified possible solutions

Parameter	Indicator	Value	Unit
Global warming: Transport	CO_2-Equivalent	0,048	Kg/ton sludge and km
Global warming: Sludge storage	CO_2-Equivalent	3,17	Kg/ton sludge and month of storage
Global warming: Plant soil	CO_2-Equivalent	-14,7	Kg/ton
Global warming: Incineration	CO_2-Equivalent	0	Kg/ton
Global warming: Drying	CO_2-Equivalent	15	Kg/ton sludge

Eutrophication: Plant soil	PO_4-Equivalent	0,53	Kg/ton sludge
Eutrophication: Incineration	PO_4-Equivalent	0,0013	Kg/ton sludge
Eutrophication: Transport	PO_4-Equivalent	0,000026	Kg/ton sludge and km
Eutrophication: Sludge storage	PO_4-Equivalent	0,161	Kg/ton sludge and month of storage

For the sludge storage only intermediate storage was included in the calculations since short term storage is part of every scenario evaluated, the intermediate storage was only assumed to be needed during the time when continuous operation was not possible. Regarding the eutrophication for drying, it was lumped together with hydrolysis in study by Grundestam et al. (2020) therefore not included in the calculations of this study since no hydrolysis is assumed in any scenario. And the global warming impact of the drying was based on data from the German company PYREG at a facility that utilizes the waste heat from the pyrolysis for the drying, and only burns biogas for the extra energy needed therefore this impact value is non conservative. The spread of heavy metals is identified as a cost but not monetized in this analysis due to lack of data, the heavy metals and other pollutant that exists in the sludge is spread out diffusely as plant soil in the reference scenario, this is discussed but not used in calculations. The global warming effects of plant soil and incineration it is assumed that in both cases the wastewater sludge is replacing peat, which has a large negative impact when it is extracted therefore resulting in a benefit. The incinerated sludge is however dried resulting in substantially less mass than what is used for plant soil and therefore the difference of this mass is used as a benefit for the plant soil creation and incineration is set to 0.

The third step is to quantify the costs and benefits that has been identified in step 2. It is important to determine an appropriate valuation method for the costs and benefits and to have proper data to get valid estimates. Monetizing qualitative parameters can however be difficult compared to products and services and the large uncertainties related to these estimates will affect the results making it less valid. The results presented in chapter 5 should therefore be considered as potential costs rather than actual prices. The reason for conducting a CBA in this thesis is to evaluate viability of the implementation of solar thermal energy in sludge drying and to evaluate the potential impact of the project in a societal perspective. The cost-benefit analysis is inspired by and can be seen as a practical application of the impact assessment for the future sludge management and phosphorus recovery that was conducted on behalf of the inquiry non-toxic and circular recycling of phosphorus from sewage sludge.

Valuation should be done from the demand side and include as much as possible of the environmental impacts related to the subjects studied. Damage costs and expressed Willingness to pay are examples of valuation methods that are considered to express societal valuation of environmental impact (Ahlroth & Finnveden, 2011). The valuation is therefore primarily based on the recommendations that are used by the Swedish Transportation Administration in ASEK 7 and the price database from the Swedish EPA. In addition to these recommendations other literature is reviewed regarding valuation of a number of environmental and health impact categories similar to those generated in the life cycle analysis by Grundestam et al. (2020), together with information retrieved by contacting companies for prices and from compilation of offers for similar projects. All monetized input parameters will be presented in the table below both with original value and the value used in this study in today's monetary value calculated by the tool from SCB based on Swedish KPI data (SCB, 2021). Together with the assumptions that have been made, only fixed prices will be used and no uncertainties is applied in the analysis.

Table 6. Monetized costs used in the CBA with reference and valuation method

Subject	Unit	Original Value	Value used in this study	Reference	Type of valuation
Investment costs solar collector field	SEK/m^2	4000	4000	Carlo Semeraro, personal communication	Price is based on small scale projects in Härnösand, could be significantly lower if field would be larger
Biogas burner and boiler	MSEK	2,5	2,5	(Baresel et al., 2016)	Based on reference facilities
Drying equipment, sludge storage, pumps and exhaust cleaning	KSEK/ Ton dewatered sludge	1,08	1,08	Huber technologies, personal communication	Based on an investment case for Huber, compared with compiled data of offers for similar projects
Operations and maintenance for solar collector field	SEK/year	1 % of capex	1 % of capex	Carlo Semeraro, personal communication	Based on experience
Operations and maintenance drying equipment	KSEK/ ton dewatered sludge	0,0175	0,0175	Huber technologies, personal communication	Based on an investment case for Huber, compared with compiled data of offers for similar projects
Biogas	SEK/kWh	0,675	0,675	(EON, 2021)	Fixed price excl VAT
Electricity	SEK/kWh	0,3771	0,3771	(HEMAB, 2021f)	Fixed price for companies from HEMAB excl VAT
Eutrophication [PO_4-Equivalent]	SEK/kg	3300	1156	(Grundestam et al. (2020), 2020; Hasselström, Johansson, Kinell, Soutukorva, & Söderqvist, 2014)	Original value is for phosphorus which has been recalculated to PO_4-ekv by multiplying with 0,3262
Global Warming [CO_2-Equivalent]	SEK/kg	7	7	ASEK 7 (Trafikverket, 2020b)	Valuation studies, shadow price, based on the reduction

					obligation fee policy instrument by the Swedish government
Traffic Safety	SEK/km	0,5	0,52	ASEK 7 (Trafikverket, 2020b)	Valuation studies of lost year of life, deteriorated quality of life, as well direct costs for property damage.
Transportation costs	SEK/ton	110	110	HEMAB, personal communication	What Kattastrand WWTP currently pays for transportation including container rent
Disposal costs dewatered sludge	SEK/ton	465	465	HEMAB, personal communication	What Kattastrand WWTP currently pays to get rid of the wastewater sludge
Disposal costs dried sludge	SEK/ton	-443,3	-443,3	(Energimyndigheten, 2021; Flaga, 2007)	Price is based on calorific value of dried sludge in combination with fuel prices for the CHP

A number of assumptions and simplifications have been made to be able to conduct the calculations. The drying equipment investment as well as operations and maintenance costs are assumed to be able to be scaled linearly with amount of sludge that the offer is given for due to lack of data for a facility with same dimensions as Kattastrand WWTP. This assumption is probably non conservative and the price would probably be higher. The drying equipment price is scaled by a factor of 1,5 to achieve redundancy in the process line as is standard for WWTPs. No regard for cost of land and increased land value are considered in the calculations. The transportation costs are assumed to be linearly scalable with the transportation time. The disposal costs for the dried sludge are negative meaning this is considered a benefit. It is the same company that operates the CHP in the city and it is assumed that the CHP can burn the dried wastewater sludge even though lacking the legal right to do so as of today. The benefit is due because it is assumed that the CHP can replace the same amount of fuel in terms of energy, that is bought to at market price thereby saving money. For the transportation calculations it is assumed that the truck can load 40 tons with an 85 % filling degree thereby moving 34 tons with each truckload, every distance is assumed to be driven back and forth.

The fourth step is computing the NPV which is the sum of all monetized and discounted benefits minus the sum of the monetized and discounted costs.

Finally, a sensitivity analysis is conducted where input parameters are changed to see how they affect the results, a sort of robustness check. In the sensitivity analysis the discount rate will be changed according to the suggestions presented in the theory chapter as well as results without greenhouse gas emissions will be evaluated to see how large impact they have on the results.

3.5 Methodology discussion

To discuss the study's credibility the well-established concepts of reliability and validity is chosen as a starting point (Alvehus, 2013). Validity is described as whether the results obtained correspond to reality or not (Shuttleworth, 2008). This report investigates an application of technology to an area where it has not yet been applied and thus the validity can be questioned, and further studies or pilot installations would be needed to confirm or condemn the validity of the results. When assumptions or simplifications are made these have always tried to be well justified. Since the CBA will be conducted with multiple qualitative parameters with diffuse monetary relationships the validity of those results will be questionable as estimates are linked with large uncertainties related to those estimates. As the valuation of environmental costs and benefits is always associated with uncertainties, the purpose of the socio-economic calculation is to show magnitudes and above all to compare the different options with each other. The results should be viewed as a potential price paid by the society in large rather than a fixed cost of the specific project scenarios.

Reliability of a study is described as how well the study can be repeated to achieve the same results (Eriksson & Wiedersheim-Paul, 2008; Shuttleworth, 2008). Since no data used in the study is primary data but instead results are based on secondary data, most of which is available to the public and other data such as retrieved from the direct contact with Kattastrand WWTP could be retrieved with an inquiry if justified, the possibility to reproduce the results are good and therefore the results deemed reliable.

4
Case study: Kattastrand WWTP

What is presented in this chapter will be the base of information for the reference alternative for the CBA and will be of use to identify other possible scenarios where sludge drying with solar thermal energy is applied. Kattastrand WWTP is located in Härnösand which is located in the northern part of Sweden. It is owned and operated by HEMAB which is fully owned by Härnösand municipality. Kattastrand's area of activity is Härnösand's urban area and reaches out to Byåker. The buildings in the area are very varied in nature, from dense urban development in the center to countryside on the outskirts. In between are residential areas with apartment buildings, villas and townhouses. The total area served is about 5000 ha. Härnösand municipality has a population of around 25 000 people but the connected number of pe to Kattastrand WWTP is just over 20 000, the treatment plant is however dimensioned for 26 000 pe (HEMAB, 2018; Härnösand kommun, 2020).

4.1 Treatment processes

The treatment processes at Kattastrand WWTP consists of mechanical treatment, chemical and biological treatment and with sand filters in the end as a final polish before it is released into the Bothnian sea (HEMAB, 2018). The mechanical treatment consists of perforated sheet metal sieves and an aerated sand trap. The next step is combined chemical and biological treatment where the wastewater is pumped to an aerated basin in which aluminum chloride is added at the end of the basin for chemical precipitation of phosphorus, this specific wastewater also requires addition of anionic polymers to get better flocculation and this is added between the aerated basin and the sedimentation basin which comes next in line (HEMAB, 2018). Here is the main sludge produced, sedimented and pumped to the sludge treatment of the treatment plant. The final step after sedimentation for the water fraction of the wastewater is filtration with sand filters before released to the recipient (HEMAB, 2018). These processes are illustrated in *figure 11*.

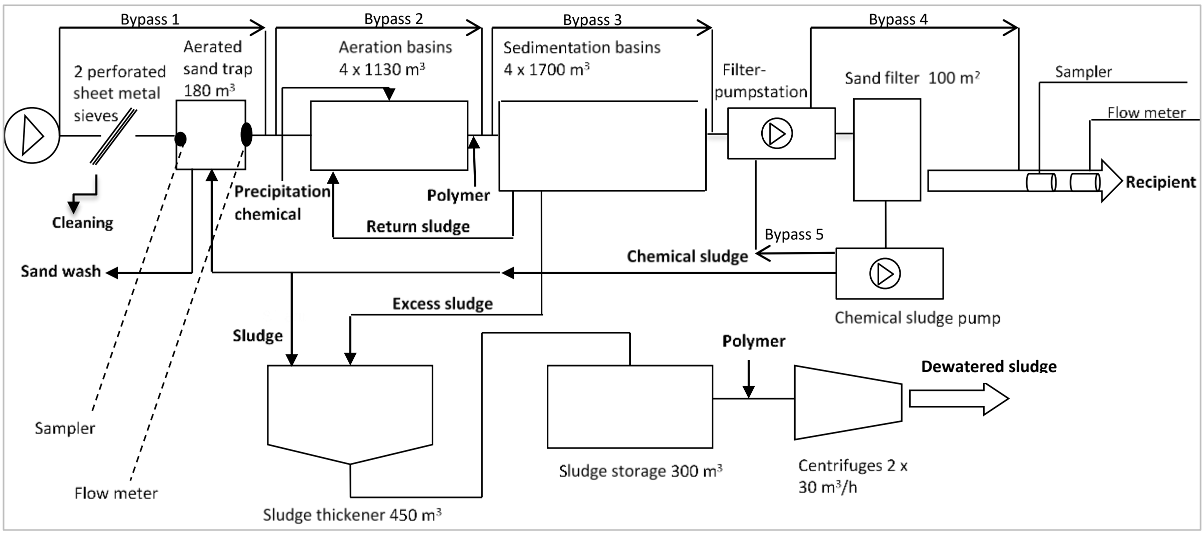

Figure 11. Process schedule of Kattastrand WWTP (HEMAB, 2018).

The processes as seen in the schedule are arranged in two lines which is a common thing amongst wastewater treatment plants for redundancy and if some process equipment needs to be stopped for maintenance.

4.2 Sludge management

The excess sludge that is produced is pumped to a sludge thickener and after that a storage before it is being dewatered in a centrifuge, before dewatering a polymer is added to make it easier to separate the water from the sludge in the centrifuge and further increase the DS of the sludge (HEMAB, 2021d). The treatment plant produces about 3400 m^3 of dewatered sludge annually which has an approximate DS content of 26 % which amounts to about 2720 tons (HEMAB, 2018). After the sludge has been dewatered it is transported with trucks to the company Markförädling i Norrland AB in Timrå where it is used to create plant soil. *Figure 12* shows the recommended transport route as recommended by google maps.

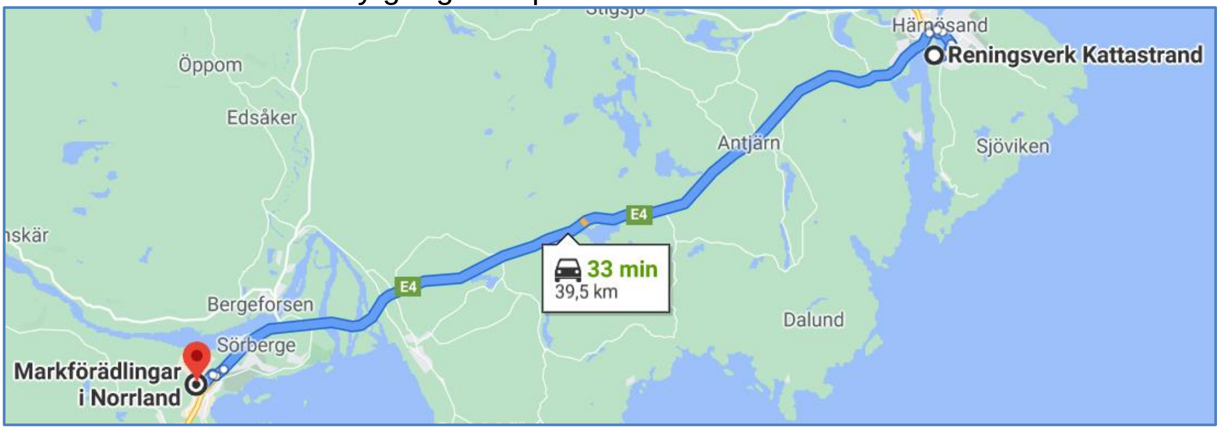

Figure 12. Transportation length between Kattastrand WWTP and Markförädling i Norrland (Google maps, 2021b).

The transport from Kattastrand WWTP to where the sludge is used to make plant soil is almost 40 km and if assuming transports with 34 tons each it results in 80 truckloads every year.

4.3 Site specific parameters

Sludge end use will depend on contamination levels as well as what type of settings that are present in the nearby area, for example if there is lots of cropland and the sludge pollution levels are below guideline values spread on arable land is possible, other factors can include if there is current infrastructure to incinerate the sludge or if there are companies that could use the sludge in a productive manner.

4.3.1 Sludge characteristics

The pollution levels of the sludge that is produced at Kattastrand WWTP is presented in *table 7* and *table 8*, this is based on data retrieved from a representative at the treatment plant.

Table 7. Sludge characteristics for Kattastrand WWTP mean and max values of monthly analyses 2019-2020 (HEMAB, 2021c).

	2019 [mg/kg DS]		2020 [mg/kg DS]	
Substance	Mean	Max	Mean	Max
Cadmium	0,46	0,69	0,52	0,8
Copper	173,57	190	169,17	190
Nickel	21,93	32	20,42	24
Lead	7,94	12	11,26	16
Zinc	265,71	300	275,83	350
Quicksilver	0,27	0,5	0,41	0,68
Chromium	43,07	66	34,58	38

	2019 [mg/kg DS]		2020 [mg/kg DS]	
Substance	Mean	Max	Mean	Mean
Total Phosphorus	13 929	17 000	13 750	16 000
Total Nitrogen	38 571	44 000	38 667	41 000

When compared with the limit values of current legislation according to SFS 1998:944 in table 2 the sludge has a lower concentration of every substance making it acceptable to be used in agriculture as long as other legislation regarding limit values in the ground and enrichment of the soil is complied with. Today HEMAB has production of biofertilizer with digestate from its biogas production facility which only uses food waste and according to information retrieved from HEMAB no farmers are willing to use the fertilizer unless it is certified according to SPCR 120 in which wastewater sludge is not allowed to be used (HEMAB, 2021a).

Table 8. Sludge characteristics for Kattastrand WWTP values of half year analyses 2019-2020 (HEMAB, 2021c).

	2019 [mg/kg DS]		2020 [mg/kg DS]	
Substance	May	November	May	November
Silver	<1	<1	<1	<1
PCB	0,0086	0,0041	0,0074	<0,004

Some values were below detection limit of the analysis method used and therefore it is just stated that those values are less than that value. Loss of ignition of the sludge is on average 73 % according to the data retrieved from the WWTP, this indicates a high carbon content (HEMAB, 2021c).

4.3.2 Geographical characteristics

The location of the specific treatment plant will affect what solutions that are a viable alternative, both in regards of end use and other factors regarding energy production for the solar collectors. What is a viable option for the end use of the sludge is determined by what quantity that is produced locally as well as in the region and what infrastructure that exists for getting rid of the wastewater sludge.

In regards of incineration of the sludge drying is required to at least 60 % DS and in the larger region there has been a proposed location for a mono-incineration plant according to *figure 13* but with under the condition that the total economy is further examined (Östlund, 2003).

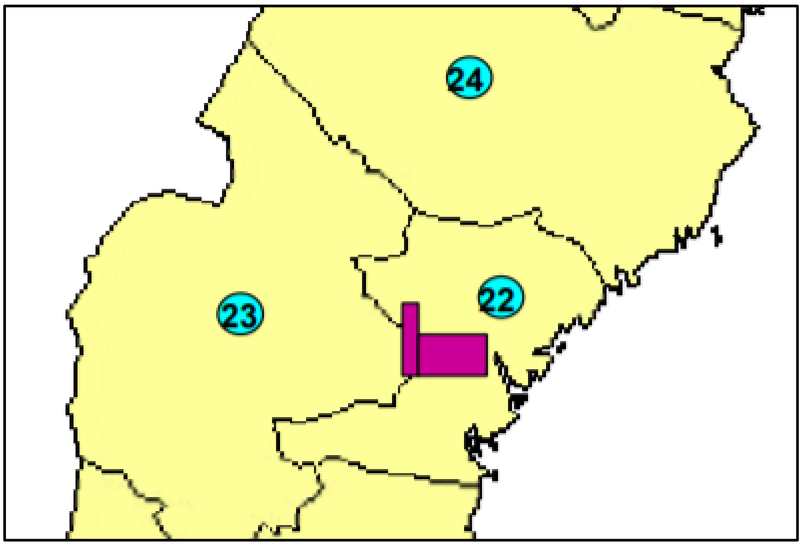

Figure 13. Suggested placement of a mono-incineration plant to serve the larger region (Östlund, 2003).

The investment costs of the suggested plant is however estimated to be around 2000 MSEK which would require cooperation between many municipalities to be able to bear the costs (Östlund, 2003). More recent indications of investment costs related to such a facility is that a mono-incineration plant would cost approximately 350 MSEK (HUBER, personal communications)

In Härnösand as mentioned before there exists current infrastructure for production of biogas but that facility does only use food waste in the production due to the end use of the digestate that is production of certified bio fertilizer through the certification system SPCR 120 in which sewage is not allowed (HEMAB, 2021a, 2021b).

The municipality also has a combined heat and power plant (CPH) in which both electricity and thermal energy for the district heating is produced. According to an operation engineer at the plant it would be technically possible to incinerate dried wastewater sludge together with the existing fuel which is primarily biofuel from the wood industry (HEMAB, 2021e). However, since wastewater sludge is considered waste incineration of the sludge requires permits which the CHP today does not have. The cogeneration plant in relation to the WWTP is seen on the map in *figure 14*.

Figure 14. Transportation length between Kattastrand WWTP and the cogeneration plant of the city (Google maps, 2021c).

Transportation length between the cogeneration plant and the WWTP is about one tenth of the current route distance.

The CHP burns wood chips, by products from the wood industry, damaged wood and peat, prices are set by the market and statistics for by products from the Swedish energy agency are shown in *figure 15*.

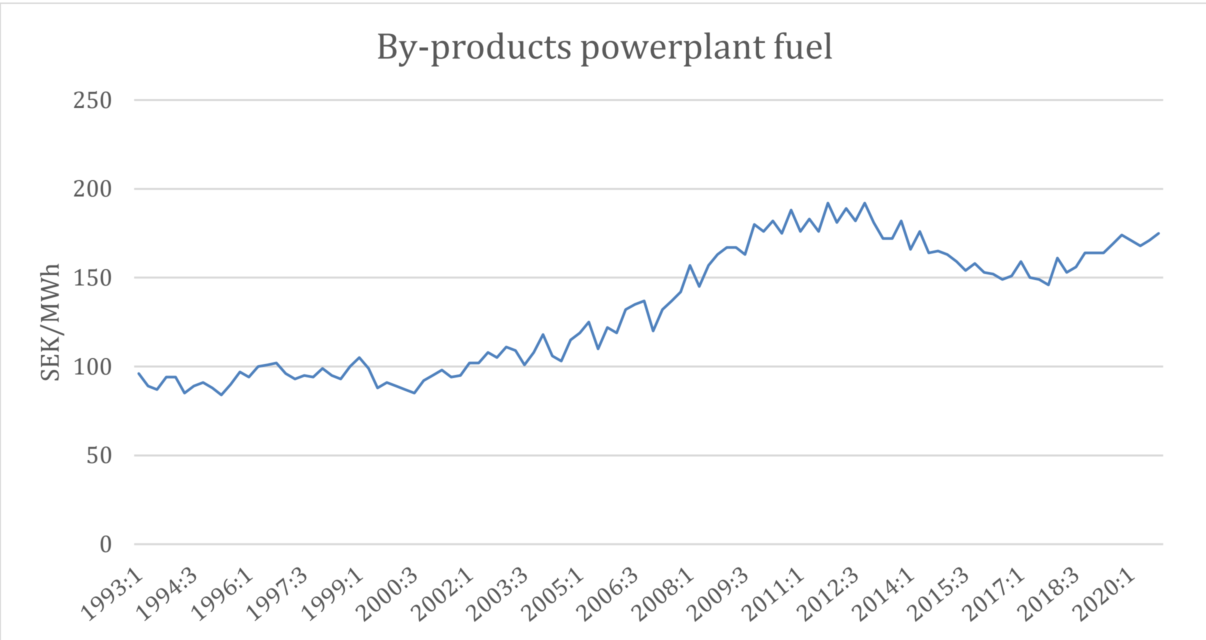

Figure 15. Quarterly prices of by products from the wood industry used as fuel for powerplants (Energimyndigheten, 2021).

The prices are volatile and varies depending on market conditions, the mean price over the time period is 133 SEK per MWh.

In Sundsvall which there exists a CPH at which waste is allowed to be incinerated and where they currently burn waste as fuel with an effect of 60 MW to be used in district heating, this is the base of their energy production (Google maps, 2021a).

Figure 16. Map presenting the CPH in Sundsvall in which waste is allowed to be incinerated (Google maps, 2021a).

The extra distance between that would be needed for transport if the end use would be incineration at Korstaverket is about 13 km compared to current management with transport to Timrå where the sludge is used to create plant soil. In Sundsvall municipality the production of wastewater sludge is about 9000 tons annually but this has not been included in any calculations.

Other site specific parameters of importance include solar irradiation and in Härnösand the global horizontal irradiance is about 950 kWh/m^2 during a year and as seen on the map in *figure 16*, where Härnösand is marked with a red circle.

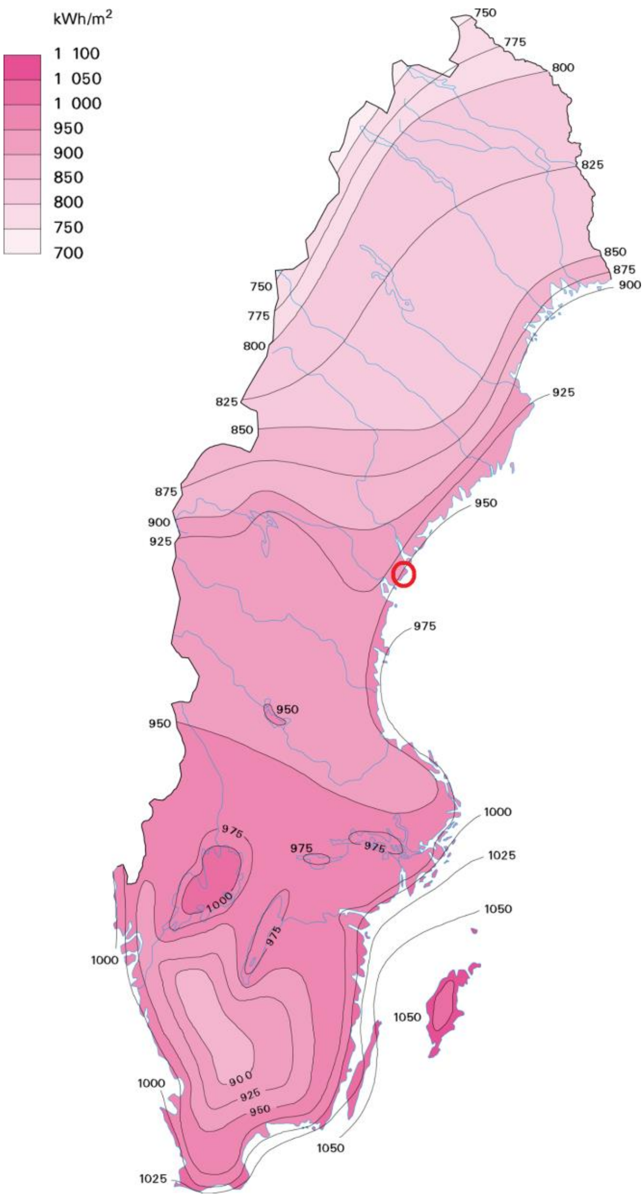

Figure 16. Map over annual global horizontal irradiance in Sweden over the period 1961-1990 (SMHI, 2009).

As mentioned in 2.2 the global horizontal irradiance consists of diffuse and direct irradiance, but it is the DNI that is of most importance to energy output for solar thermal collectors. Data retrieved from Absolicon of local energy production is presented in *figure 17* for different operating temperatures.

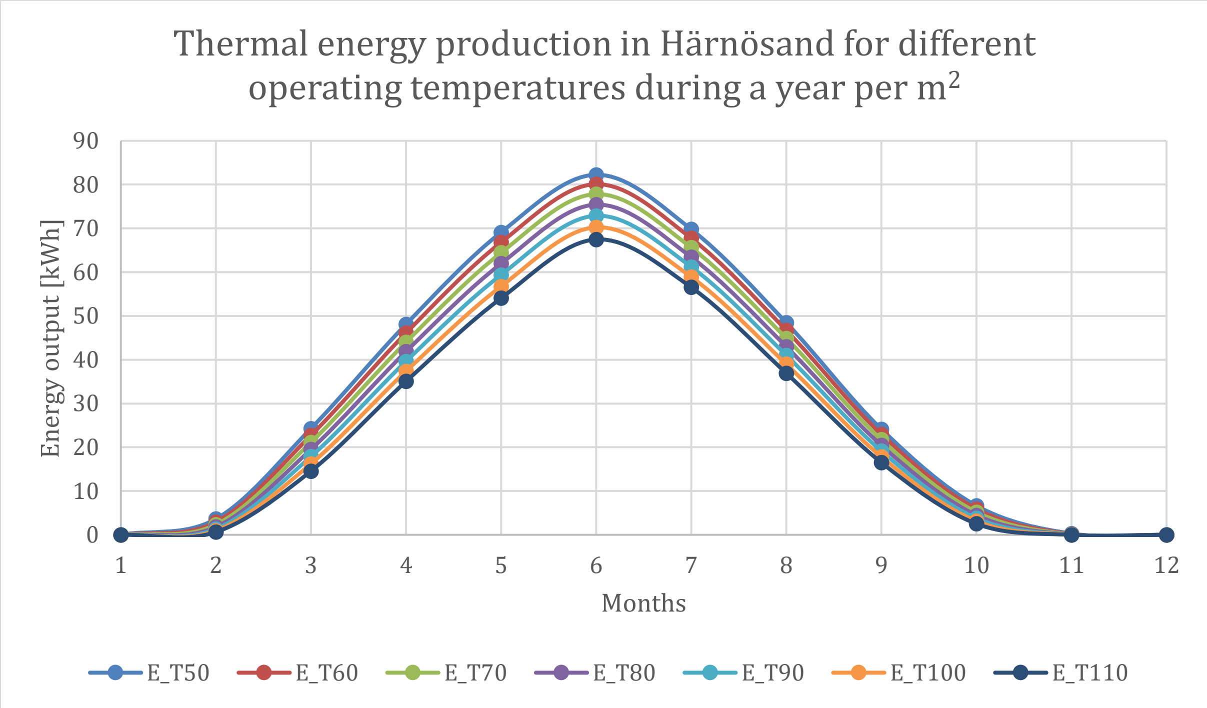

Figure 17. Monthly energy output from Absolicons T160 solar collector in kWh per m^2 aperture area during a year in Härnösand.

The sum of the energy output for a year is shown in *table 9* for the different operating temperatures.

Table 9. Annual energy output for different operating temperatures in Härnösand

Temperature [°C]	Energy output per year and m^2 [kWh/m^2]
50	377
60	362
70	347
80	332
90	316
100	300
110	284

Lower temperatures yield a higher energy output but in terms will affect the sludge drying capacity.

5
Results

In this chapter the results according to the aim of the thesis will be presented. The first part of the chapter will be to present identified scenarios of how solar thermal energy could be used in the sludge drying process and to define the reference alternative that will be used in the CBA. Then the results of the CBA process will be presented which will be the basis of the discussion that will follow.

5.1 Reference alternative and identified solutions

Since there exists well proven and mature sludge drying technologies that are driven by thermal energy in the same temperature span as is possible to achieve with solar thermal collectors and that integration of various energy sources is a common thing in sludge drying it is clear that solar thermal energy fits well to this purpose. One of the issues with solar thermal energy is that the energy production occurs when the sun is shining and primarily during the summer, especially at Nordic latitudes such as at Härnösand. This in relation to that the demand is continuous results in a discrepancy for the supply and demand in terms on energy and could either be solved by storing energy, the wastewater sludge or by utilizing multiple energy sources and only using solar thermal when it is available. These conditions are the base of the scenarios that are evaluated in the CBA. The drying is assumed to have a thermal energy demand of 0,85 kWh / kg of stripped water and an electricity demand of 0,049 kWh/kg of stripped water and is dried to a DS of 90 % to maximize the calorific value of the final product.

5.1.1 The reference alternative

This is the current management at Kattastrand WWTP and is based on the information presented in chapter 4 together with the assumptions and estimates that has been presented in chapter 3. In *table 10* the sums of the annual costs and benefits for the reference alternative are presented.

Table 10. The monetized costs and benefits for the reference alternative

Item	Unit	Value
Project economics total	SEK/year	1 564 000
Disposal	SEK/ton	465
Transportation	SEK/ton	110
Global warming total	SEK/year	-106 015
Transportation	Kg CO_2-eq/year	10 444,8
Plant soil	Kg CO_2-eq/year	-25 589,8
Eutrophication total	SEK/year	1 673 030
Transportation	Kg PO_4-eq/year	6
Plant soil	Kg PO_4-eq/year	1442
Traffic safety total	SEK/year	3328
Total investment cost	SEK	0
Total annual cost	SEK/year	3 134 343

The current management has zero investment costs but continuous annual operational costs and benefits. The highest cost item is eutrophication and after that comes the disposal costs. Global warming is negative meaning it is a benefit due to the assumption that the wastewater sludge is replacing peat which has a large negative climate impact when it is extracted.

5.1.2 Scenario 1: Sludge drying with 100 % solar thermal energy

In this scenario an alternative with sludge drying powered by 100 % solar thermal energy is evaluated. The dewatered wastewater sludge is assumed to be stored during October to February and drying operation only occurs when energy is produced starting in February until the end of September. It is assumed that the dried sludge can be burnt at the CHP in Härnösand as is technically feasible even though no current permit exists, the dried sludge is assumed to replace the same weight and calorific value of peat that is currently burnt at the CHP.

Table 11. The monetized costs and benefits for scenario 1

Item	Unit	Value
Project economics total investment	SEK	20 309 154
Project economics total annually	SEK/year	-135 691
Drying equipment plus necessities	SEK	4 406 400
Solar field system plus necessities	SEK	15 902 754
Operation and maintenance	SEK/year	230 346
Electricity	SEK/year	32 166
Disposal	SEK/year	-434 108
Transportation	SEK/ton	37
Global warming total	SEK/year	128 243
Transportation	Kg CO_2-eq/year	376
Incineration	Kg CO_2-eq/year	0
Storage	Kg CO_2-eq/year	17 944
Eutrophication total	SEK/year	1 055 273
Transportation	Kg PO_4-eq/year	0,2
Incineration	Kg PO_4-eq/year	1,27
Storage	Kg PO_4-eq/year	911,4
Traffic safety total	SEK/year	60
Total investment cost	SEK	20 309 154
Total annual cost	SEK/year	1 047 884

The disposal costs are considered a benefit as it is assumed to replace material with the same energy value that are bought at market price for the CHP therefore resulting in annual savings. The solar collector field size is calculated based on the 90 degree operating temperature annual production. The results show that both the investment cost as well as annual operational costs are rather large compared to the reference alternative and the other scenarios evaluated.

5.1.3 Scenario 2: Sludge drying with 100 % biogas

Biogas is produced locally in Härnösand as well as a common byproduct of WWTPs and therefore a natural option for fuel for a thermal energy demand. Kattastrand WWTP does however not produce any biogas and therefore this is assumed to be bought at market price according to what has been presented in chapter 3 and 4. Using biogas as fuel does not require intermediate storage of the sludge and therefore eliminates those items as continuous operation is possible. Potential costs for this scenario are presented in *table 12*.

Table 12. The monetized costs and benefits for scenario 2

Item	Unit	Value
Project economics total investment	SEK	6 906 400
Project economics total annually	SEK/year	554 247
Drying equipment plus necessities	SEK	4 406 400
Biogas burner and boiler	SEK	2 500 000
Operation and maintenance	SEK/year	71 318
Electricity	SEK/year	32 166
Biogas	SEK/year	848 966
Disposal	SEK/ton	-434 108
Transportation	SEK/ton	37
Global warming total	SEK/year	288 232
Transportation	Kg CO_2-eq/year	376
Incineration	Kg CO_2-eq/year	0
Drying	Kg CO_2-eq/year	40 800
Eutrophication total	SEK/year	1707
Transportation	Kg PO_4-eq/year	0,2
Incineration	Kg PO_4-eq/year	1,27
Traffic safety total	SEK/year	60
Total investment cost	SEK	6 906 400
Total annual cost	SEK/year	844 246

As no storage is needed those large items are removed, however large amounts of biogas are required giving a high annual cost for the thermal energy demand which compared to scenario 1 is paid for as an investment cost.

5.1.4 Scenario 3: Sludge drying with 50/50 biogas and solar thermal energy

In this scenario a combination of scenario 1 & 2 is assumed where the drying is powered with solar during the period when that energy is available and powered with biogas the rest of the time. This would require investments in both biogas burner, boiler as well as in a solar collector field system but with a smaller dimension of the solar collector field. This result in larger investment costs compared to scenario 2 but lower than compared to scenario 1 and since the cost potential of the intermediate sludge storage are removed as continuous operation is possible the costs for eutrophication and global warming are minimized.

Table 13. The monetized costs and benefits for scenario 3

Item	Unit	Value
Project economics total investment	SEK	14 857 777
Project economics total annually	SEK/year	209 033
Drying equipment plus necessities	SEK	4 406 400
Biogas burner, boiler and solar field	SEK	10 451 377
Operation and maintenance	SEK/year	186 491
Electricity	SEK/year	32 166
Biogas	SEK/year	424 483
Disposal	SEK/ton	-434 108
Transportation	SEK/ton	37
Global warming total	SEK/year	145 432
Transportation	Kg CO_2-eq/year	376
Incineration	Kg CO_2-eq/year	0
Drying	Kg CO_2-eq/year	20 400
Eutrophication total	SEK/year	1707
Transportation	Kg PO_4-eq/year	0,2
Incineration	Kg PO_4-eq/year	1,27
Traffic safety total	SEK/year	60
Total investment cost	SEK	1 485 777
Total annual cost	SEK/year	356 232

With continuous operation no storage is needed as was a large cost item in scenario 1, utilizing solar heat during the summer minimizes the need to buy biogas and results in a larger investment but with lower annual costs.

5.2 Net present value of the 3 scenarios

The discount rate of the analysis is 3,5 % but other rates are evaluated in the sensitivity analysis to get an idea of how large impact that assumption has on the results. The expected lifetime of the solar collector field is 25 years and that timespan is therefore used when calculating the NPV of the scenarios that has been presented. This timespan might be lower for the drying equipment but for comparability the same lifespan is assumed. The net present value after 25 years is presented in *figure 18* as a cumulative graph showing how the NPV increases over time to get an idea of how many years it takes for the investments to become profitable.

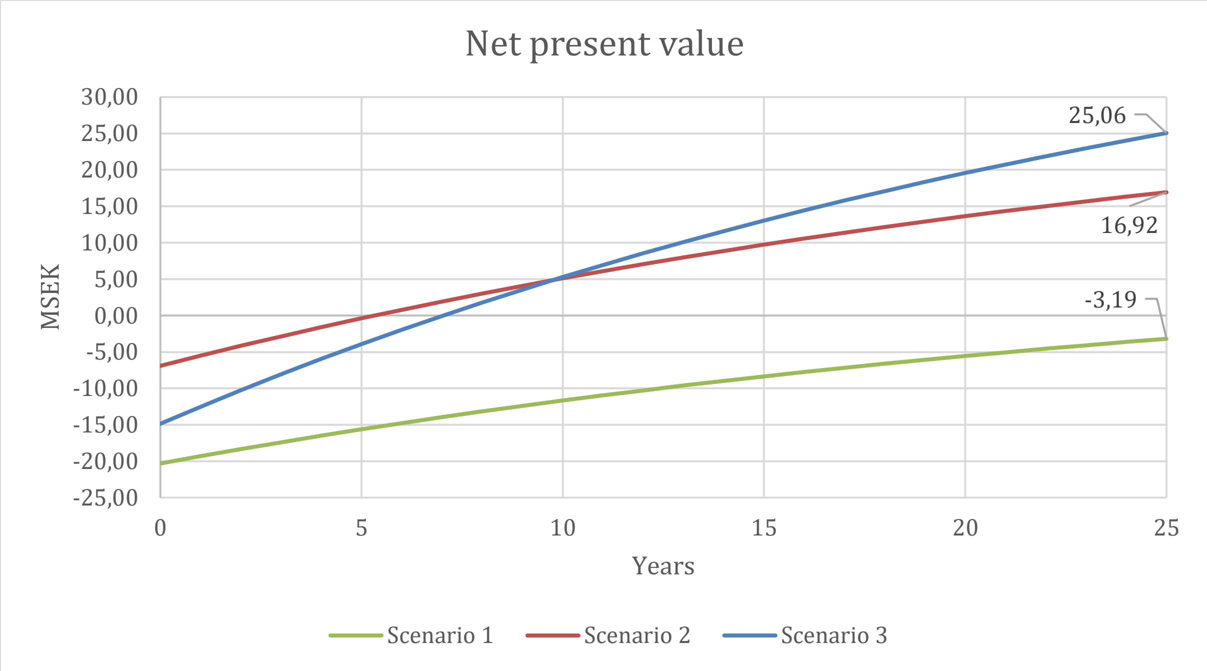

Figure 18. NPV of the 3 evaluated scenarios

Scenario 1 does not become profitable over its lifetime as the NPV at 25 years is still negative and the most profitable option is scenario 3. Scenario 2 gets a positive NPV at year 6 and scenario 3 at 8 years.

5.3 Sensitivity analysis

One of the factors that largely influence the NPV is the discount rate, to evaluate the impact of this factor the same calculations as above are conducted with a discount rate of 1 % instead of the 3,5 % that was used earlier.

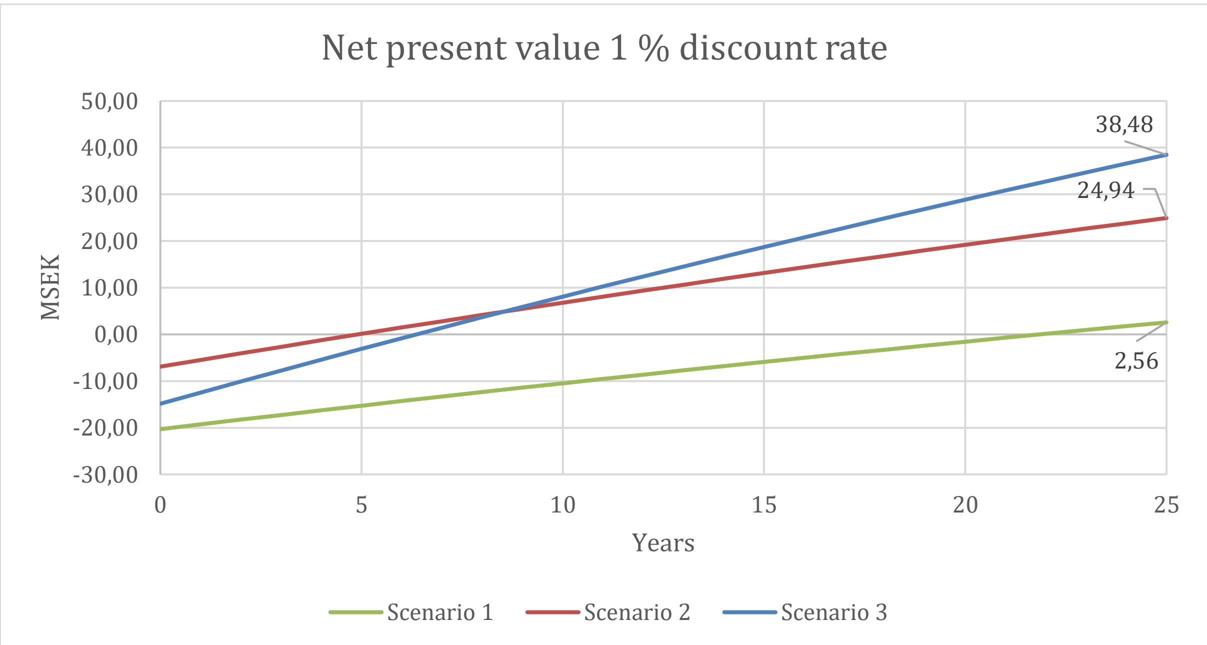

Figure 19. NPV with 1 % discount rate

The results are similar to what is seen earlier with a more linear type of graph. With a discount rate this low all the scenarios become profitable and scenario 3 still has the highest NPV at 25 years.

To evaluate what impact each category has on the NPV the NPV is calculated for each price category and plotted for each scenario. This shows what group of cost items that contribute to the final NPV and how these evolve over time. This is done with a discount rate of 3,5 %.

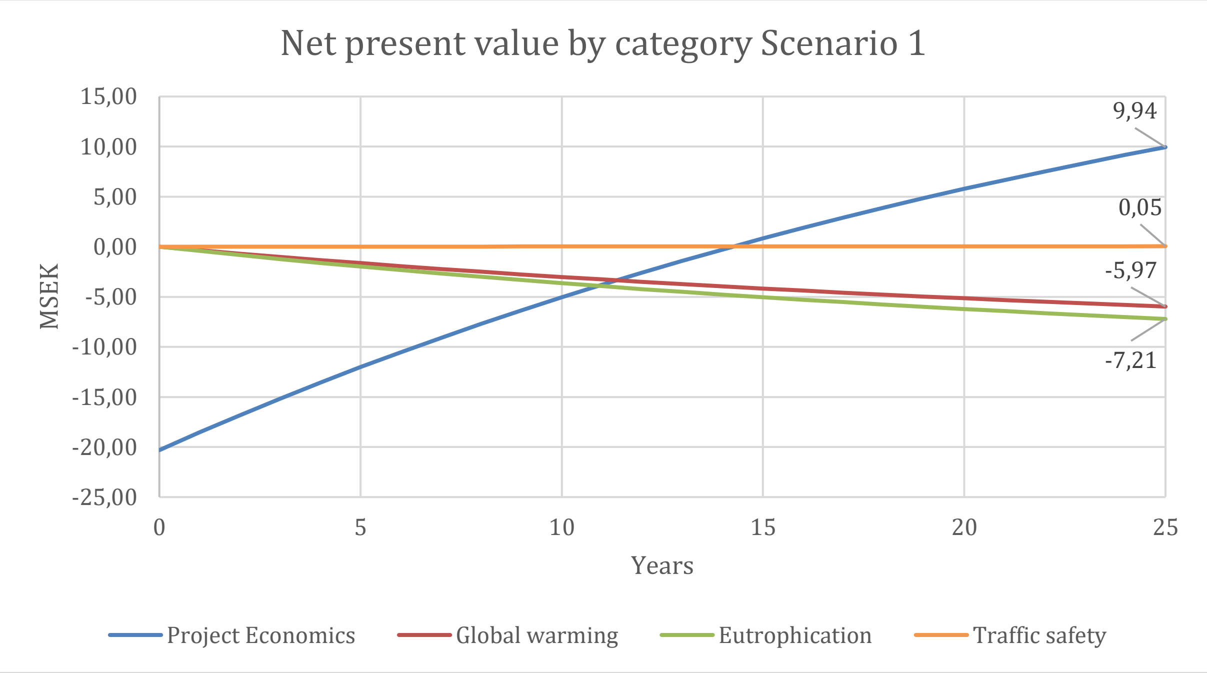

Figure 20. NPV for scenario 1 split by category

For scenario 1 it is the project economics that are the most beneficial and the largest positive contributor to the NPV at 25 years. Traffic safety is almost negligible and eutrophication and global warming has a negative contribution.

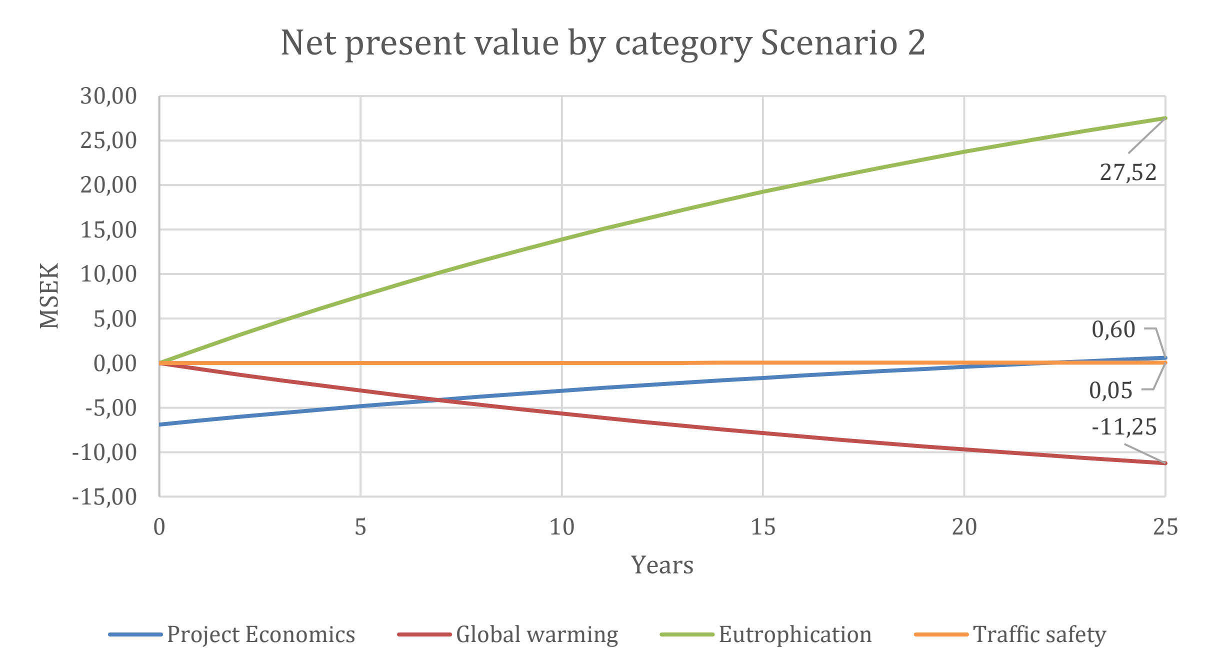

Figure 21. NPV for scenario 2 split by category

For scenario 2 eutrophication has a very large positive contribution to the NPV while project economics and traffic safety are almost negligible. The only negative contributor is the global warming category.

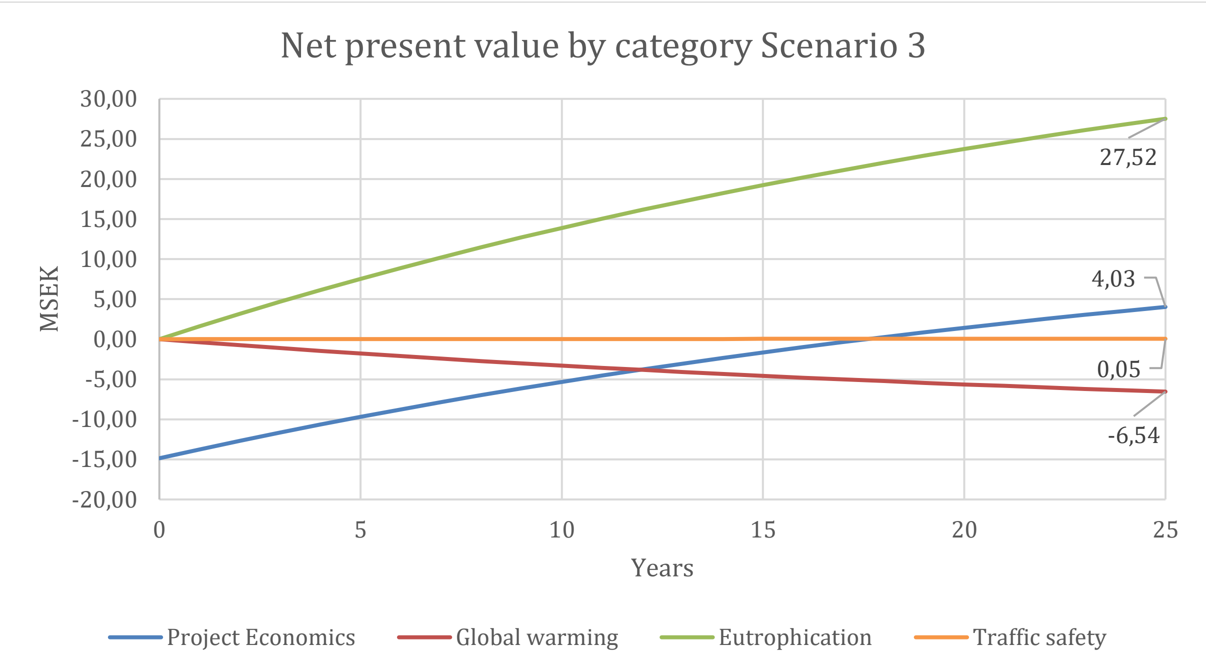

Figure 22. NPV for scenario 3 split by category

The third scenario is somewhat similar to the second except for the slightly more positive project economics category and slightly less negative factor or global warming. The eutrophication still has a very large impact on the final NPV.

As many of the qualitative parameters are associated with large uncertainties a calculation of the NPV for only the project economic category is conducted. These are actual costs and savings that the municipal energy company would have if these solutions were implemented. The results should still be viewed as potential rather than factual as these numbers also are associated with uncertainties and simplifications.

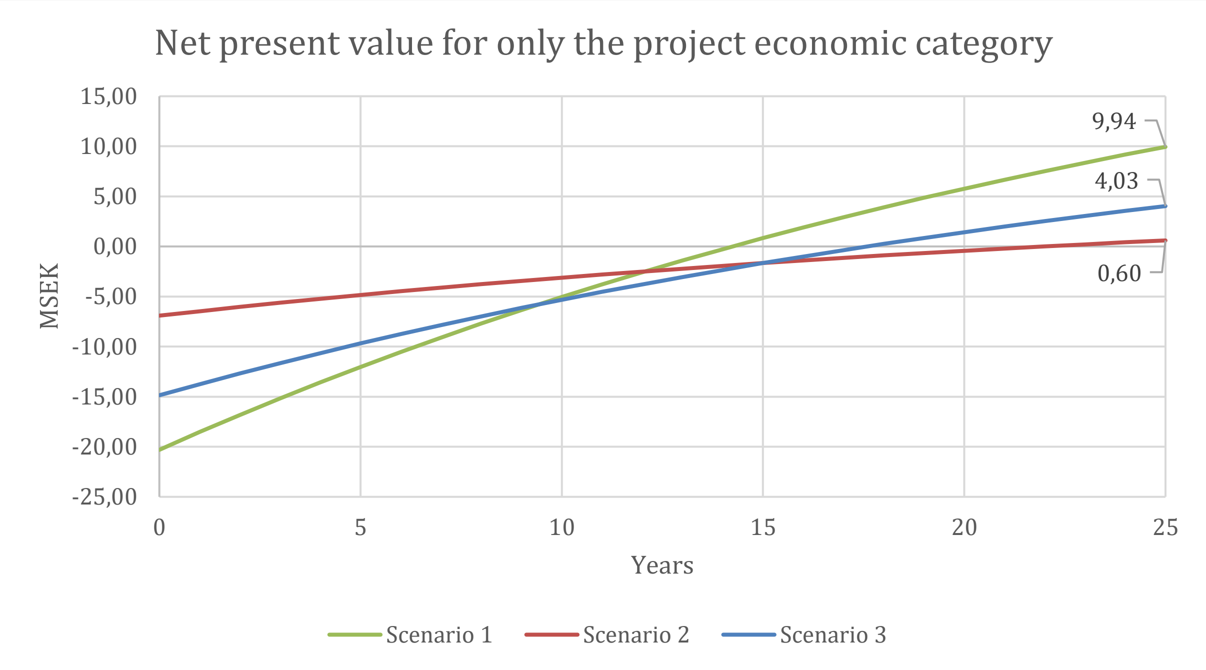

Figure 23. NPV for the project economics with a discount rate of 3,5 %.

Only looking at the project economics the scenario with 100 % solar powered sludge drying is the most profitable at 25 years. The least profitable scenario is scenario 2.

To further evaluate the project economics the cost item related to the disposal and savings that the CHP would get from not having to buy fuel at market price is evaluated. Instead of using the mean price of the timeseries presented in chapter 4 the lowest fuel price, 84 SEK/MWh, is used and the same calculations as above is conducted with the results presented below.

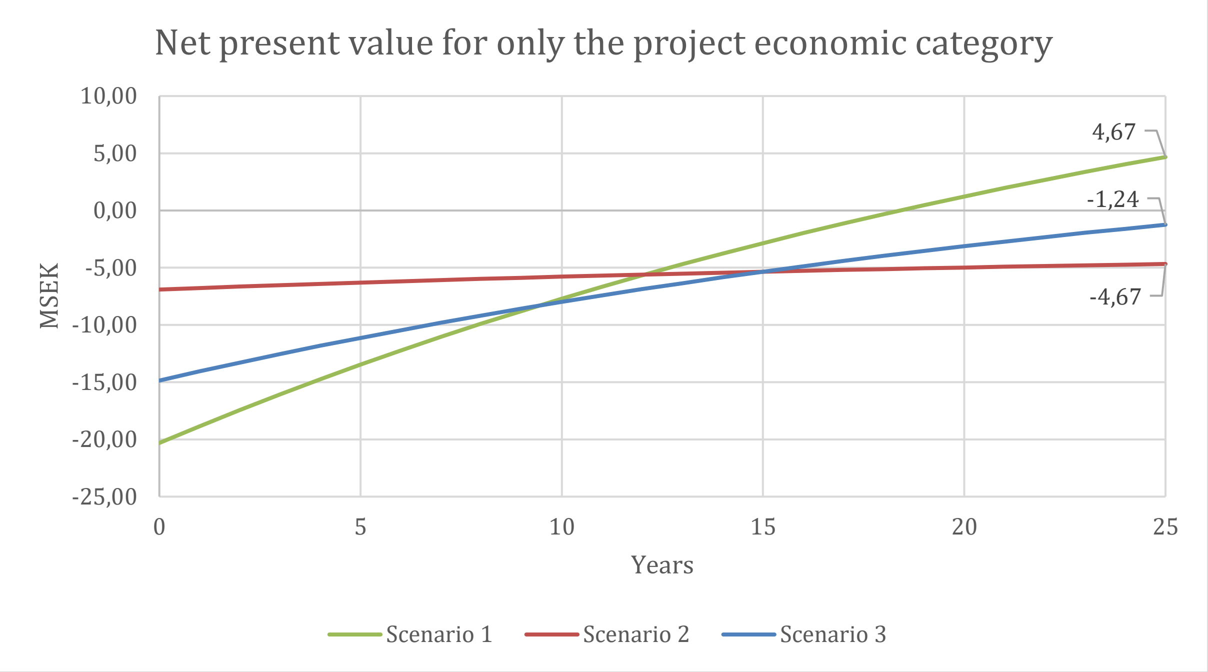

Figure 24. NPV for the project economics with a discount rate of 3,5 % and assumed lowest fuel price for replaced fuel at CHP.

The results show that the only profitable option would be scenario 1 with a positive NPV of 4,67 MSEK at the end of the expected lifetime.

6 Discussion

The primary result of this study is the NPV at the end of the expected lifetime of the different investment scenarios for implementing sludge drying at Kattastrand WWTP. This together with the supportive information in the theory and case study chapter gives a holistic economic decision support. It breaks down risks and effects from different management options into economic cost potential. Although environmental aspects were taken into consideration and monetized there could be other perspectives that are not reflected upon in the model, perspectives of economical budgets, politics and social factors, that could have a large impact on decisions of this character. The scenarios that are evaluated are not optimized in an economical sense and there are most likely other scenarios that are more realistic options if the municipality of Härnösand would implement sludge drying and incineration as a management strategy. A large facility would probably be more economical sustainable and could serve the larger region including Sundsvall and perhaps other municipalities as well but if that would be evaluated in the future these results may still give inspiration and an indication of how such a management strategy could be designed. The results are as mentioned earlier associated with large uncertainties and once more it should be stressed that the results should be considered as potential costs and benefits that the society as a whole would pay or receive.

6.1 Results discussion

The results of a cost-benefit analysis are always encumbered with simplifications and assumptions that has a great impact and this thesis is not an exception. There are major sources of error that can impact the results of the different scenarios and reference alternative is both positive and negative ways. A large difficulty with cost-benefit analysis is to decide what items to monetize and what valuation method to use. This study used the results of the life cycle analysis by Grundestam et al. (2020) as a base source for the values used in the analysis, this is motivated by the fact that it is a recent study in the same field of study from a credible source. Some items are however not included and should be further discussed because it impacts the final results. The spread of heavy metals and other pollutants is an unwanted effect when creating plant soil from wastewater sludge. The sludge contains pollutants that do not disappear when using the sludge in the soil and the final use of the soil is diffuse therefore these contaminants get spread in the environment with low traceability and could be of harm to both the environment and humans. Many of the contaminants are persistent and is therefore enriching the environment with unwanted substances which could be leached to nearby watercourses or groundwater. This was not monetized in this study due to lack of data but is identified as yet one more reason the change the current sludge management of Kattastrand WWTP. The manufacturing of equipment has environmental costs as well and is not included in the results, that would require a life cycle analysis of the products that are used and is outside the scope of this thesis. Furthermore, it is noticed that the eutrophication stands for a large impact of the results, this is highlighted in the sensitivity analysis but still considered motivated to be used in the results as done by Grundestam et al. (2020).

The cost benefit analysis does not include uncertainty in this thesis instead the results are to be seen as potential costs and benefits as mentioned earlier. The analysis could be conducted as a Monte Carlo simulation with the inclusion of probability distributions and uncertainty intervals to provide even more in-depth results.

Another point of discussion the distribution of costs and benefits, who actually pays the price of certain items and who receive the benefits. In this study the Swedish taxpayer is the one who bears the financial burden, the municipal company would pay the investment and operational costs but this would be financed with taxes and water and sewer fees. This would be a local cost to pay as it is governed by the municipality. The traffic safety is a minor cost item but also would be a local issue. The emissions from transport and sludge storage are a global problem in terms of climate change and not something that would or could be locally paid for. Eutrophication problems would most likely be paid regionally but possibly by the region around the Baltic sea as many nutrients usually end up in the sea if spread nearby.

6.3 Recommendations for future work

Recommendations for future studies on the topic is to optimize the economics of the analyzed scenarios, include a larger region with multiple WWTPs as an implemented solution like this most likely would benefit from a larger volume and scale of the facility. Also, further economical optimization of what proportion of solar compared to biogas that would be most beneficial as well as do dynamical simulations of the energy demand and supply for the drying operation.

In addition to this it would be recommended to do a Monte Carlo simulation to get a deeper understanding of the uncertainties that are related to the results and how to get a deeper understanding of how risks could be reduced.

7
Conclusion

The theoretical background provides information about how the current wastewater sludge management in Sweden could face a major disruption due to legislation and that this would require reorganization of two thirds of today's sludge handling. This would most probably result in an increase in sludge drying and incineration as proposed by the public inquiry and as that require substantial amounts of thermal energy it essential to find sustainable ways to operate these facilities. Thermally driven sludge drying equipment exists and are mature technologies and they are operated in the same temperature span as small parabolic through solar collectors. This in combination with the praxis to use different heat sources depending on the local settings of the plant makes solar thermal a solution with great potential to be utilized in sludge drying. The viability of such an implementation is deemed as good based on the results of this study, however perhaps not as a single source solution but if combined with other heat sources the implementation has obvious benefits compared to not using solar thermal energy. The results show that sludge storage has large emission potential and gives an indication that perhaps it is more efficient to include a heat storage instead, this is however not evaluated in this study and would require further analysis to be determined. If multiple heat sources are utilized it is possible to have a continuous drying operation and thus removing the emissions associated with intermediate storage of dewatered sludge, at the same time this would result in a large decrease in annual costs since the renewable source of energy is used during the summer when the energy is abundant. The dried sludge could be stored and incinerated resulting in cost savings for local heat power plants and solving the disposal problems of wastewater sludge at the same time. The ashes from the incineration can after that be stored to later be used in phosphorus recycling in compliance with the suggested legislation for sustainable sludge management in Sweden. Sludge drying with solar thermal energy is a scalable solution that shows great potential in northern Sweden and thus in countries with more solar irradiation probably would have even larger potential and benefits. With further optimization of the economics in combination with doing an analysis including the whole region of interest the implementation of combined solar and biogas powered sludge drying is a sustainable alternative for the future wastewater sludge management of Sweden and internationally.

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