Master's Thesis

Master:
Water Science and Management

Wastewater sludge treatment, energy recovery and sustainability:

the Waternet case

Student:

Sara Giorgi, 5504023
s.giorgi@students.uu.nl
sara.giorgi1989@gmail.com
+31644677713

UU Supervisor:

Patrick Smeets
Patrick.Smeets@kwrwater.nl

Internship organisation:

Waternet

Internship supervisors:

Hans van Fulpen
Hans.van.Fulpen@waternet.nl

Enna Klaversma
enna.klaversma@waternet.nl

Universiteit Utrecht

waternet
waterschap amstel gooi en vecht
gemeente amsterdam

Abstract

Sludge production and handling have always been the most challenging components of wastewater treatment. Sludge disposal is the most expensive and energy intensive treatment, and now that the Netherland's focus is on CO_2 reduction (with the goal to be carbon neutral by 2020), research on this topic is needed more than ever.

The present research is two-fold. The first part focuses on primary sedimentation; from previous research, it emerged that for a wastewater treatment plant serving 46,000 PE it is much cheaper to not implement it and provide for the extra energy demand by means of solar panels. This study enquired on whether this is true also for much bigger scales (i.e. 500,000 PE). The second part focuses on sludge treatment, and whether it is more sustainable to digest and dry the sludge or to dry it directly, in both cases with the production of a biofuel destined to the cement industry. Primary energy and CO_2 reduction potentials were calculated. This was enquired on both with an upstream situation including primary sedimentation and one not including it. What emerged is that indeed, primary sedimentation is not convenient even for scales as big as 1 million PE; even then, solar panels are a cheaper measure to reduce the plant's carbon footprint. In regard to final sludge handling, it emerged that if only secondary sludge is present, it is better to not digest it and directly dry it; when the sludge is mixed, it is better to digest both primary and secondary sludge prior to drying.

However, when a future situation as close as 2020 is analysed (with the use of waste heat and updated conversion factors for CO_2 and primary energy), it turned out that when both primary and secondary sludge are present, it is better to digest primary sludge only. Further research is needed to determine whether the most sustainable alternative is also financially convenient when compared to other sustainability measures like solar panels.

Acknowledgements

I would first like to thank Patrick Smeets, my UU supervisor, for his guidance and precious advice throughout the writing of my thesis.

Hans van Fulpen and Enna Klaversma, my supervisors in Waternet, who allowed me to carry out my research and taught me a lot during the process.

The colleagues from Waternet, who spent some of their time with me to help clear my doubts, teach me and show me around the treatment plants: Peter Piekema, Bas de Nijs, Lex Lelijveld, Alex Veltman, Gijs van der Meer, Marcel Zandvoort and Manon Bechger.

Kees Roest from KWR, for his time and explanations.

Ronnie Berg and Berend Reitsma from Tauw, for their precious contribution to the first part of my research.

Otto Reinstra and Frank Smits, for introducing me to Waternet and helping me get my internship.

Table of contents

Abbreviations

AD: Anaerobic Digestion
AEB: Afval Energie Bedrijf
bCOD: biodegradable COD
BOD: Biochemical Oxygen Demand
CO_2: carbon dioxide
CHP: Combined Heat and Power
COD: Chemical Oxygen Demand
CSI: Centrale Slibontvangst Inrichting
DWF: Dry Weather Flow
$e_{D,AD}$: energy demand for anaerobic digestion
$e_{D,ASP}$: energy demand for activated sludge aeration
$e_{D,O}$: energy demand for other equipment
$e_{D,PS}$: energy demand for primary sedimentation
$e_{D,SS}$: energy demand for secondary sedimentation
e_R: energy recovery
ECN: Energieonderzoek Centrum Nederland
GER: Gross Energy Requirement
GHG: Greenhouse Gases
GWP: Global Warming Potential
LCA: Life Cycle Assessment
LHV: Lower Heating Value
$m_{bCOD-CH4}$: bCOD converted in methane in the anaerobic digester
$m_{bCOD-SN}$: bCOD in the supernatant line
m_{BS}: mass of sludge entering the dewatering process
$m_{CO_2;AD}$: mass flow of CO_2 in the biogas
$m_{CO_2;ASP}$:mass flow of CO_2 in the activated sludge off-gas
$m_{CO2;CH4comb}$: mass flow of CO_2 due to methane combustion
$m_{DIG,in}$: mass of sludge entering the digester
$m_{CO_2eq;fugitive}$: mass flow of CO_2-eq due to fugitive emission
m_{PS}: mass of primary sludge
m_{SS}: mass of secondary sludge
PE: Population Equivalents
PE: Primary Effluent (in Figure 1.1)
PEF: Primary Energy Factor
PI: Primary Influent
PS: Primary Sludge
RWF: Rain Weather Flow
SS: Secondary Sludge
SSK: Standaardsystematiek voor Kostenramingen
TPS: Thickened Primary Sludge
TSS: Thickened Secondary Sludge
UCT: University of Cape Town
VAT: Value-Added Tax
VS: Volatile Solids
WWTP: Wastewater Treatment Plant

Glossary

Anaerobic digestion.	Process by which bacteria degrade organic matter and convert it to biogas (methane and carbon dioxide) in absence of oxygen.
Biochemical oxygen demand.	Amount of oxygen needed by aerobic bacteria to break down the biochemically oxidisable matter in the water.
Biological reactor.	In an activated sludge process, reactor in which bacteria degrade part of the organic matter and remove the nitrogen from the wastewater; it comprises an anoxic tank, an anaerobic tank and an aerated tank.
Centrate.	Reject water separated from sludge after the dewatering step.
Chemical oxygen demand.	Amount of oxygen needed to chemically oxidise all the organic matter in the water.
Combined heat and power.	Power generation technique that produces electricity and also efficiently recovers the heat generated in the process (and can be used in district heating, for instance).
Dewatering.	Mechanical process applied to remove part of the moisture content in the sludge; it normally achieves a dry solids percentage of around 20-25% and is carried out by means of centrifuges or filter presses.
Dry weather flow.	Flow of wastewater during dry weather; it only comprises wastewater coming from households and industries.
Dry solids.	Total dry matter (fixed and volatile) present in the sludge.
Dry solids concentration.	Percentage of dry solids in sludge expressed as weight.
Fixed solids.	Inorganic fraction of the dry solids in the sludge; also called ash content.
Gross Energy Requirement.	Measure of the energy content of raw materials including the primary energy needed for production and transport.
Lower heating value.	Heat released by a substance under combustion, net of the energy needed to evaporate the moisture content.
Polyelectrolytes.	Water soluble polymers used in sludge treatment as an aid for dewatering and thickening.
Primary energy.	Energy naturally present in nature and that has not been subjected to any kind of transformation (fossil fuels, solar energy, etc.).
Struvite.	Phosphate mineral (NH4MgPO4·6H2O) which crystallises in presence of magnesium in wastewater and wastewater sludge. It is sometimes purposefully formed, collected and used as a granular fertiliser.
Thickening.	Mechanical process implemented after the settled sludge is collected and that concentrates it to around 4-6% dry solids; normally performed with gravity thickeners (primary sludge) or belt thickeners (secondary sludge).
Volatile solids.	Organic fraction of the dry solids in the sludge.

Waste heat.	Low temperature heat produced during the conversion of fossil fuels to usable energy and not useful anymore in that process.
Wet weather flow.	Flow coming to the wastewater treatment plant during wet weather; it comprises wastewater coming from households and industries and runoff water.

1. Introduction

One of the most relevant impacts of climate change will be on water. Water will be more abundant in some regions, scarcer in others and some think wars over water are likely to happen (Barnaby, 2009). As now widely acknowledged by the scientific community, one of the main contributors to climate change are greenhouse gas emissions, mainly caused by energy production from fossil fuels (Min, Zhang, Zwiers, & Hegerl, 2011). In turn, the management of water (and in particular wastewater) depends on energy (Frijns, Mulder & Roorda, 2009).

Within the European Union, 1991 saw a benchmark in water protection legislation. In this year the Urban Waste Water Treatment Directive was adopted which regulated the collection and treatment of municipal and industrial wastewaters prior to discharge. It compelled the Member States to collect and apply at least secondary treatment to the wastewaters from all the agglomerations of 2,000 or more PE (Population Equivalents) and to apply more advanced treatment for areas of more than 10,000 PE and sensitive areas (Council Directive 91/271/EEC of 21 May 1991 concerning urban waste-water treatment [1991] OJ L135).

As mentioned, purifying water entails the implementation of treatments that are energy intensive; the needed energy use feeds the loop of greenhouse gas (GHG) emissions and therefore contributes to climate change and its impacts on water itself.

In light of this scenario, several efforts have been made to render the water sector more efficient in terms of energy use and, therefore, of GHG emissions. This is particularly true for the Netherlands (Frijns, Hofman, & Nederlof, 2013).

Table 1.1 shows the yearly global warming potential (GWP) of the Dutch water sector (Frijns et al., 2009). As it can be seen, the wastewater segment is the one that contributes to global warming the most and thus the improvement of which could create the biggest positive impact.

Table 1.1. Yearly warming potential of the Dutch water sector.

Drinking water	436,875	tonnes CO_2-eq	26	%
Sewerage	123,620	tonnes CO_2-eq	7	%
Wastewater	1,114,.310	tonnes CO_2-eq	67	%
Total	1,674,805	tonnes CO_2-eq	100	%

Waternet is the water company that manages the entire water cycle for Amsterdam and its wider area; it is the joint venture between the municipality of Amsterdam and the Amstel, Gooi en Vecht water board. One of the goals of the company is to be climate neutral by 2020. In order to do so, a reduction of the tonnes of CO_2 emitted (directly or indirectly) needs to be achieved, which can be of three types:

- Direct GHG emissions (from the wastewater treatment facilities);
- Indirect GHG emissions coming from energy use (production at the fossil fuels power plant, transport related fossil fuel use);
- Other indirect GHG emissions (i.e. from the production of chemicals used in the processes, building materials, etc.). (Klaversma, van der Helm, & Kappelhof, n.d.).

As a water cycle company, Waternet also manages the treatment of wastewater, and one of their sub goals is to implement treatment processes in a way that reduces the overall GHG emissions.

Figure 1.1 shows the layout of a typical activated sludge wastewater treatment plant (WWTP), also referred to as UCT (University of Cape Town) scheme in this study. The figure also shows the water flows, the organic matter flows (represented by the COD, Chemical Oxygen Demand), the energy flows and the GHG flows. All the symbols used can be found in the Abbreviations page. Not shown, is a thickening step before the digester.

Sludge as a product from wastewater treatment plays a big role in this scenario. We define sludge as the solids/water mixed liquor deriving from the treatment of wastewater. It comprises primary sludge (PS), consisting of the fraction of settling solids (m_{PS} in Figure 1.1), and SS, secondary (or activated) sludge (m_{SS} in Figure 1), resulting from the secondary (biological) treatment. The sludge composition depends on the type of sewer (combined or separate), on the source of wastewater (domestic or industrial) (Casey, 2006), and on the type of wastewater treatment (with normal aeration tanks, Nereda technology, etc.) (personal communication, Enna Klaversma).

Sludge treatment and disposal is one of the costliest aspects of water treatment (Babatunde, & Zhao, 2007; Casey 2006). Its global production is growing with time because of population growth and ever more stringent water purification standards, making its disposal increasingly challenging. However, sludge is not simply a waste product; it is in fact a potential source of energy, as it constitutes mostly of degradable organic matter and therefore biochemical energy (Frijns et al., 2013).

The amount of energy that can be recovered from sludge (and therefore the CO_2 reduction that can be achieved) depends on several factors, among which are the composition of the sludge (COD fractionation, primary or secondary sludge) and the method that is used to retrieve the energy (digestion and what type, incineration) (Metcalf & Eddy, 2003).

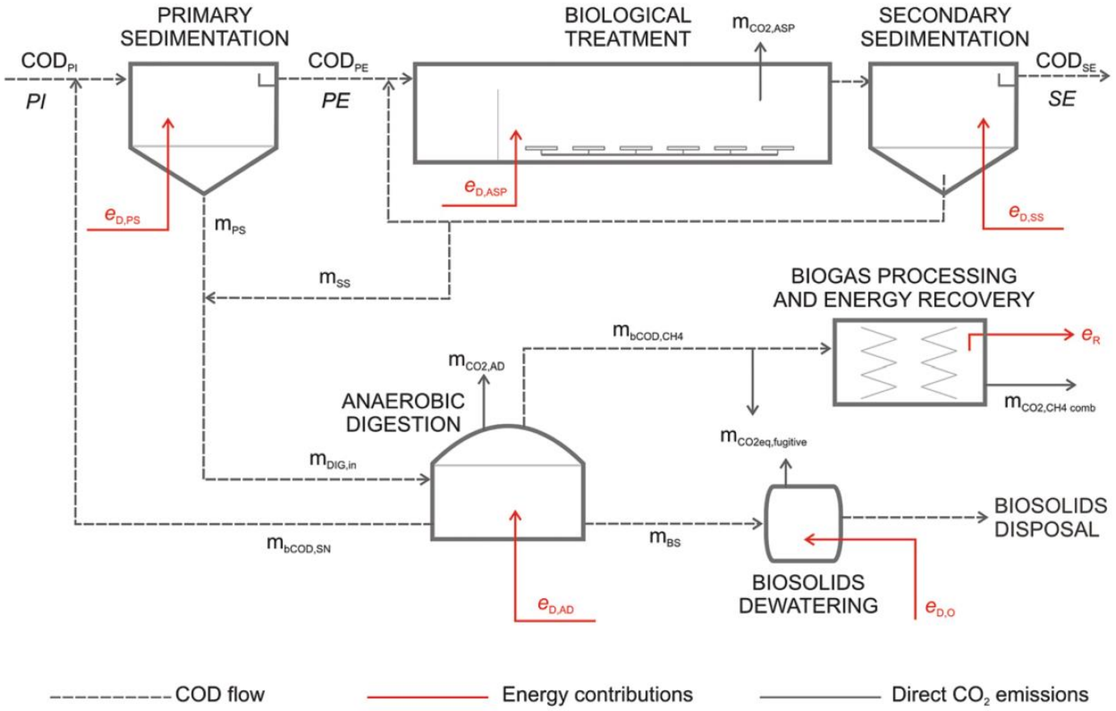


Figure 1.1: UCT scheme, with COD, energy and $CO_{2\text{-}eq}$ flows (Gori, Jiang, Sobhani, & Rosso, 2011).

Because of the aforementioned reasons, Waternet has an interest in researching potential improvements measures that could be taken regarding sludge, for possible applications in future WWTPs or retrofitting of the existing ones. The two main objects of this study are therefore primary sedimentation (the presence of which will influence the energy recovery from sludge) and energy recovery from sludge alternatives.

1.1 Primary sedimentation

Primary sedimentation is a pre-treatment normally applied to medium and large WWTPs designed according to the activated sludge process (UCT) (Gori, Giaccherini, Jiang, Sobhani, & Rosso, 2013). It is a physical process aimed at removing part of the readily settleable solids before the raw wastewater is fed to the biological reactor. It is normally implemented in circular (Figure 1.2) or rectangular tanks and if the design is optimal, a percentage of 50 to 70% removal of the suspended solids (corresponding to a 25 to 40% BOD (Biological Oxygen Demand) removal) can be achieved (Metcalf & Eddy, 2003).

Applying primary sedimentation has two positive effects: it reduces the amount of organic matter that needs to be broken down in the aerated tank (hence reducing the oxygenation needed, hence the energy) and yields primary sludge, which has a much higher biogas yield than secondary sludge (Gori et al. 2013; Gavala, Yenal, Skiadas, Westermann, & Ahring, 2003; van Loosdrecht, Kuba, van Veldhuizen, Brandse, & Heijnen, 1997). According to Metcalf & Eddy (2003), biogas production from the digestion of primary sludge is double the one from activated (secondary) sludge. From biogas, energy can be recovered in a combined heat power (CHP) generator; biogas has a composition of around 65% methane and 35% carbon dioxide.

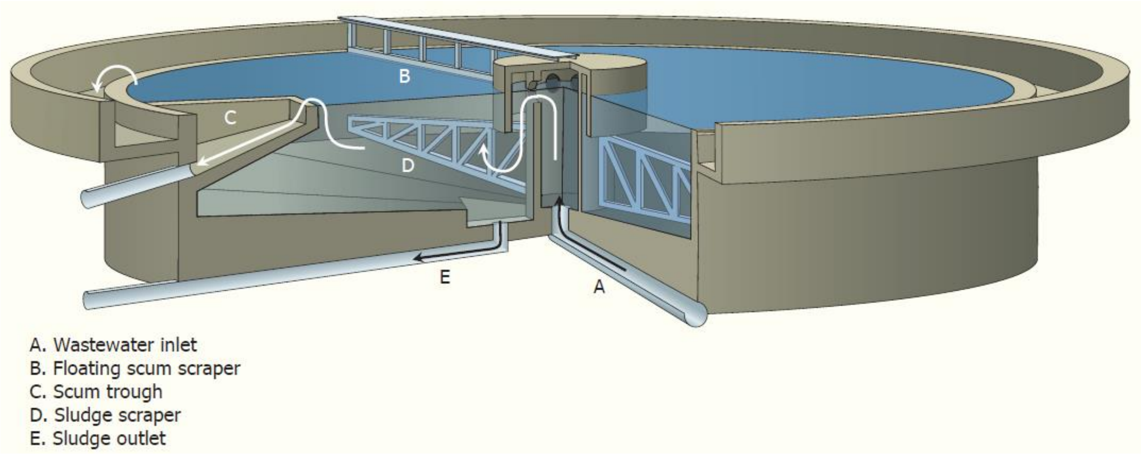
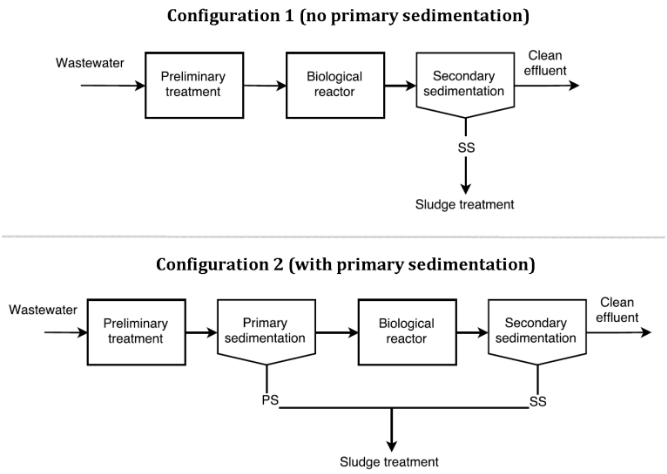


Figure 1.2: Schematic representation of a circular primary sedimentation tank (TU Delft, n.d.).

Therefore, as demonstrated in several studies (among others, Gori et al. 2013), applying primary sedimentation reduces significantly the energy deficit of the plant, and thus its carbon footprint. However, it can easily be deduced that the facilities needed to apply primary sedimentation (namely sedimentation tank(s), pumps, etc.) have a certain yearly cost, given both by maintenance and depreciation. The concrete and the other construction materials and potential chemicals used to enhance the sedimentation are also connected to CO_2 emissions.

A study was conducted by Waternet to design the new treatment plant in Weesp (46,000 PE), the sludge of which will be treated in an off-site location (Amsterdam West's WWTP, situated in the north-western part of the city). It emerged that, as expected, the configuration with primary sedimentation (which in this study will be called configuration 2) has a lower carbon footprint (given by the lower energy deficit) but a higher yearly cost compared to the one without (configuration 1). Therefore, the price per kilogram of CO_2 saved was calculated and for a plant of that size, it is cheaper to match the carbon offset through the use of other forms of renewable energy (i.e. solar panels). This forces the designer to rethink the traditional approach (which includes primary sedimentation). It is important to mention that this is true for the case of Waternet; in other cases, prices and costs may differ in such a way that the opposite could be true. Figure 1.3 shows the treatment schemes for the two configurations.


Configuration 1 (no primary sedimentation)

Configuration 2 (with primary sedimentation)

Figure 1.3: Scheme of configuration 1 and 2.

1.2 Sludge and energy recovery

Agricultural use of the sludge in the Netherlands is never practiced because of the highly stringent standards imposed by the Dutch regulation for heavy metals, pathogens, toxic elements, etc. (Mininni, Blanch, Lucena, & Berselli, 2015). The usual final disposal of sludge is incineration, typically preceded by anaerobic digestion (AD) with the final goal of biogas recovery (personal communication, Enna Klaversma). Several sludge conditioning techniques can be implemented to enhance the digestion; however, this requires energy or chemicals.

Waternet's policy on sludge handling is to mesophilically digest the sludge (process for which the sludge needs to be heated to 35 °C). Biogas is recovered (with CHP) and subsequently the digested sludge is first mechanically dewatered (in centrifuges) and then sent to an incinerator. The energy retrieved from the incineration of the sludge's dry solids matches the one needed to evaporate the moisture content (as high as 78%); therefore, incineration of digested sludge is energy neutral (personal communication, Enna Klaversma).

However, as mentioned before, primary sedimentation is not always convenient and secondary sludge (which will be the only sludge produced by a plant with no primary sedimentation) has quite a low biogas yield (Lu & Ahring (2007) state that primary sludge can yield for some processes almost four time as much biogas as the secondary sludge). By contrast, raw (non-digested) secondary sludge contains quite a lot of organic matter that would all be readily available for combustion. An alternative to digestion with subsequent incineration could therefore be the creation of a biofuel by simply drying the non-digested sludge with waste heat to a very high dry solids concentration (personal communication, Enna Klaversma). This biofuel could be used for instance in cement kilns, where both the energy and the inorganic materials are recovered. This way, the sludge would not have to be digested (digestion requires energy to heat up the sludge) and all the organic energy present in the sludge would all be burnt in the incineration process.

Another important aspect connected to AD and energy recovery is that not all the biogas produced is used for energy production. In fact, leakages occur in several percentages (up until 10% of biogas production) (Daelman, van Voorthuizen, van Dongen, Volcke, & van Loosdrecht, 2012; Yoshida, Mønster, & Scheutz, 2014; Hjort-Gregersen, 2014 and others). This leads to direct emissions of methane, a GHG with a GWP 25 times that of CO_2 on a 100 years' time scale (IPCC, 2007), which contributes to the overall carbon footprint of the process and it cannot be ignored when assessing the sustainability of the treatment. According to

Daelman et al. (2012), the effects of the direct emission of leaked methane can exceed the benefits connected to the valorisation of the biogas.

Figure 1.4: Left, Amsterdam West's digestion tanks (www.wabag.com); right, AEB's incinerator (www.aebamsterdam.com).

It is therefore worthwhile investigating whether the current policy applied by Waternet is the most efficient in terms of energy recovery and therefore the most sustainable, especially in light of a possible abandonment of primary sedimentation.

1.2.1 Literature review: sludge handling routes

While in literature many studies can be found about the environmental impact of different final sludge handling routes, none of them, to the author's best knowledge, can be directly applied to the Dutch (and Waternet's) situation. Most of the studies reviewed included as a final disposal land spreading or landfilling (Hospido, Moreira, Martín, Rigola, & Feijoo, 2005; Houillon & Jolliet, 2005 amongst others) and none of them considered secondary sludge only. Hong, Hong, Otaki, & Jolliet (2009) considered several final handling routes both with and without AD and concluded that applying AD before incineration has a higher global warming impact. However, only mixed sludge is considered and no drying step is taken into account. Besides, as stated by Murray, Horvath, & Nelson, (2008), energy balances for sludge are highly dependent on site specific conditions.

The most used method to assess the environmental impact of the alternatives seems to be Life Cycle Assessment (LCA). Among the most recent, Alyaseri & Zhou (2017), Gourdet et al. (2017) and Yoshida et al. (2014). These studies, although their results cannot be applied directly to Waternet's case, are a good starting point to assess the alternatives.

Some studies (Yoshida et al. 2014; Clavreul, Baumeister, Christensen, & Damgaard, 2014; Naroznova, Møller, & Scheutz, 2016) performed the LCA by using the EASETECH software, developed by Technical University of Denmark. This tool models LCAs for waste flows management, including sewage sludge, and allows for different scenarios which can include, among others, emissions to the environment.

1.3 Research questions

From the problem description above, a research question arises, which stems in two separate but related sub-questions:

In Waternet's case, how do the choices of the sludge related processes impact the sustainability (and the economy) of the whole wastewater treatment cycle?

1. Is there a scale at which primary sedimentation is financially convenient to reduce the energy deficit, when compared to other methods of clean energy production (i.e. solar panels)? If yes, what is this scale? What are other sensitivity factors that influence the choice at the found size?
2. What should the final sludge handling process be: sludge digestion plus incineration, or sludge drying with the creation of biofuel? If there is a scale at which primary sedimentation is more convenient, could a potential different treatment method be applied to primary and secondary sludge, depending on their different energy yields?

2. Methods and data

The approach utilised for the calculations is based, in principle, on energy and mass balances. For the CO_2 balance, short-cycle carbon dioxide was not considered. Through the use of calculation spreadsheets, these balances were performed and the results analysed and visualised.

The data were supplied by different sources. However, since the nature of water and sludge treatment is highly dependent on the local and specific conditions, wherever possible data from Waternet's operational registries and experiments were used. Where these were not available, values from literature were retrieved.

2.1 First research question: primary sedimentation

2.1.1 Plant size analysis

To answer the first sub-question, a new plant has been analysed with the capacity of 500,000 PE (UCT system, biological removal of phosphorus), to find out whether for this scale primary sedimentation becomes convenient. This study was carried out mainly by upscaling from the values used in the study for the 46,000 PE plant for Weesp.

The design parameters (influent flow rate, sludge quantity, biogas production, etc., originally calculated with the same tool used to design WWTPs) were scaled up linearly (from Table A1.1 to Table A1.8, Appendix 1). Table 2.1 offers a summarised overview. The sludge characteristics (biogas yield, solids content, energy content etc.) are relative to the sludge treated by Waternet and are shown in Table 2.2, together with the parameters which determine the energy recovery from sludge. It is important to highlight that the total amount of dry solids produced by the two configurations (and the amount of organic solids) slightly differs in the two configurations.

Table 2.1. Overview of main dimensioning parameters.

Parameter	Unit of measure	Basis		Scale up	
		No pr. sed (conf.1).	With pr. sed. (conf. 2)	No pr. sed (conf.1).	With pr. sed. (conf. 2).
Load (à 150 g COD)	PE	**46,000**		**500,000**	
Max flow rate	m^3/h	1,800		19,565	
Average flowrate	m^3/d	11,860		128,913	
DWF flowrate	m^3/d	9,128		99,217	
DWF period	h	14		14	
DWF flow rate	m^3/h	652		7,087	
COD load	kg/d	4,889		53,141	
BOD load	kg/d	1,925		20,924	
Suspended Solids load	kg/d	2,674		29,065	
N-kjeldahl load	kg/d	440		4,783	
P-total load	kg/d	63		685	
Pre sedimentation tank surface	m^2		475		5,163
Max primary sludge production	kg ds/d		2,674		29,065
Thick. Surface (Prim. Sludge)	m^2		33.4		363
Effective V of pr. sludge buffer	m^3		119		1,304
Volume anaerobic tank	m^3	1,304		14,174	
Volume anoxic tank	m^3	836	1,024	9,087	11,130

Volume aerobic tank	m^3	6,480	3,314	70,435	36,022
Design excess sludge production	kg ds/d	2,426	1,424	26,370	15,478
Oxygenation	kgO_2/h	439	364	4,772	3,957
Surface secondary settler	m^2	2,115		22,989	
Total capacity of exc. Sludge pumps	m^3/d	523	321	5,685	3,489
Total flow rate (belt thickener)	m^3/h	33.4	20.4	363	222
Max dry solids load (belt thickener)	kg ds/h	330	200	3,587	2,174
Avg flow rate to s.s. buffer	m^3/d	50	31	543	337
Effective volume of s.s. buffer	m^3	200	122	2,174	1,326

Table 2.2. Sludge characteristics.

Parameter	Value	Unit of measure
PS solids reduction during digestion	45	%
SS solids reduction during digestion	25	%
PS biogas production	1000	m^3/tonds
SS biogas production	700	m^3/tonds
Electricity production from biogas	6.1	kWh/Nm^3
Energy demand of dewatering (Ams West)	80	kWh/tonds
Solids content of dewatered sludge	22	%
Fixed solids fraction of dewatered sludge	30	%
Energy content of dried organic sludge	21.662	GJ/tonDOS
Moisture evaporation energy needed	3.2	GJ/tonH_2O
Incinerator's efficiency	24	%

The direct building costs were calculated mainly scaling up from the Weesp situation; the scaling up method used for the single parts (investment costs) is shown in table 2.3. The direct investment costs for the small scale Weesp plant and some of the facilities' costs for the 500,000 PE one were calculated by Tauw (an external consultancy company) with the use of a calculation model called SSK ("Standaardsystematiek voor Kostenramingen"). The predicted construction costs, the total investment costs and the yearly costs given by depreciation and maintenance were calculated using the same factors as for Weesp.

A complete overview of the investment costs (Table A2.1) and the basic assumptions used for the cost calculations (Table A2.2) can be found in Appendix 2.

Energy demand (Table A1.9, Appendix 1) was scaled up linearly and the data about the amount of concrete were provided by Tauw (Table A1.11, Appendix 1). The linear upscaling is applied to those quantities that grow linear with size. The squared upscaling (following the square-cube law) is applied to quantities like for example buildings. The quantity of concrete in a building of 2 m^3 is not double that of one of 1 m^3, but it is $\sqrt{2}$ (2 being the ratio between the two volumes). The same principle is applied to costs.

The costs of sludge handling, the price rate for energy and the biogas production rates and selling prices are relative to the Waternet case. A table with the basic assumptions can be found in Appendix 2 (Table A2.2).

The assumption regarding sludge treatment is that the thickened sludge leaves the plant and is transported to Amsterdam West. Here it is digested (with subsequent biogas production and CHP), dewatered and then incinerated, together with household solid waste, in the adjacent AEB (Afval Energie

Bedrijf, “waste-to-energy company”), with which Waternet has as a contract. The tariff of sludge handling contains costs (for dewatering, phosphate removal, etc.) and profits such as biogas production and struvite production. Capital Expenditures (Capex) costs were included in the sludge handling costs to reflect the fact that for such an amount of sludge, a new sludge handling facility should be built.

Table 2.3. Investment costs of the facilities and scaling up methods.

Facilities	Civil	Mechanical	Upscale unit
Influent pumps	Squared	Squared	m^3/h
Sand trap + sand washer	Squared	Squared	m^3/h
Bar screen	-	Squared	m^3/h
Primary clarifier	SSK sheet	Squared	m^2
Primary sludge pump	-	Squared	m^3/h
Blower building	Multiplied by a factor 2	-	
Activated sludge tanks	SSK sheet	Linear	m^3
Aeration tank mixers and pumps	-	Linear	m^3/h
Secondary clarifiers	SSK sheet	Squared	m^2
Recirculation sludge pumps	Squared	Squared	m^3/h
Primary sludge thickener	Squared	Squared	m^2
Primary sludge buffer tank	Squared	Squared	m^3
Primary sludge thickener pumps	-	Squared	m^3/h
Belt thickener building	Multiplied by a factor 2	-	
Excess sludge pumps	-	Squared	m^3/h
Belt thickener	-	Squared	m^3/h
Secondary sludge thickener pumps	-	Squared	m^3/h
Secondary sludge buffer tank	Squared	Squared	m^3

The yearly costs of each configuration comprise of depreciation costs (calculated with the annuity method), maintenance costs and operational costs like energy use, personnel costs, sludge handling costs and costs of chemical used (Table 2.4).

Table 2.4. Overview of construction, investment, and yearly costs (500,000 PE).

		No primary sedimentation		With primary sedimentation	
Construction and building costs					
Part					
Civil		€	41,014,000	€	46,400,000
Mechanical		€	22,693,000	€	26,238,000
Electrical		€	9,077,000	€	10,495,000
Process Automation		€	2,269,000	€	2,624,000
Total expected construction costs		€	75,054,000	€	85,756,000
Total investment costs	incl. VAT	**€**	**127,967,000**	**€**	**146,215,000**
Yearly costs					
Depreciation					
Part					
Civil	incl. VAT	€	4,099,000	€	4,637,000

Mechanical	incl. VAT	€	3,573,000	€	4,131,000
Electrical	incl. VAT	€	1,429,000	€	1,653,000
Process Automation	incl. VAT	€	667,000	€	772,000
Total depreciation	incl. VAT	**€**	**9,769,000**	**€**	**11,192,000**
Operational costs					
Part					
Civil maintenance	incl. VAT	€	248,000	€	281,000
Mechanical maintenance	incl. VAT	€	824,000	€	952,000
Electrical maintenance	incl. VAT	€	330,000	€	381,000
Process Automation maintenance	incl. VAT	€	82,000	€	95,000
Unforeseen maintenance	incl. VAT	€	148,000	€	171,000
Energy costs	incl. VAT	€	1,287,000	€	1,228,000
Personnel costs	incl. VAT	€	500,000	€	500,000
sludge processing costs (PS)	incl. VAT		-	€	2,770,000
sludge processing costs (SS)	incl. VAT	€	4,593,000	€	2,804,000
AlCl3 (30.7%)	incl. VAT		-	€	149,000
Polyelectrolytes (42%)	incl. VAT	€	103,000	€	60,000
Total operational costs	incl. VAT	**€**	**8,115,000**	**€**	**9,391,000**
Total yearly costs	incl. VAT	**€**	**17,884,000**	**€**	**20,584,000**

The carbon footprint of each configuration is given by the indirect CO_2 emissions related to: reinforced concrete of facilities, polymer electrolytes use, aluminium consumption, sludge transport and energy use and production. The factors used to convert the impacts to the kgCO_2 equivalent were retrieved from the Ecoinvent database (Wernet et al., 2016). Values are shown in Table 2.5. The one used to convert kWh to kgCO_2-eq (0.67 kgCO_2/kWh) is the value for “grey” (from fossil fuels) energy production. It is however worth mentioning that the actual sources of energy could be different (green, mixed). To assess the real substitution value, the real energy sources to be substituted should be researched. For these calculations, that value was used as it was the same for the small plant (46,000 PE).

Table 2.5. CO_2 contributions.

Contributor	**Factor**	**Unit of measure**	**No pretr.**	**With pretr.**
Reinforced concrete	0.057	kg CO_2/kg concrete	97,668	97,333
Polyelectrolytes consumption	2.13	kg CO_2/kg PE active	249,608	239,044
Aluminium consumption	0.537	kg CO_2/kg $AlCl_3$	0	162,782
Sludge transport	0.115	kg CO_2/ton.km	589,954	803,418
Energy in total	0.67	kg CO_2/kWh	9,019,545	8,633,400
Energie out total	-0.67	kg CO_2/kWh	-3,869,504	-6,629,267
Energy (net)	0.67	kg CO_2/kWh	5,150,041	2,004,133
CO_2 balance		kg CO_2/year	**6,087,271**	**3,306,710**

Once the total costs of the two configurations and their carbon footprint were calculated, the cost of sustainability was computed as the ratio between the difference in yearly costs and the difference in yearly CO_2 production. In addition to this, the cost of energy production (allowed for by the implementation of primary clarification) was calculated as the ratio between the difference in yearly costs and the difference in yearly energy demand:

$$Sustainability\ (CO2\ reduction)\left[\frac{€}{CO_2}\right] = \frac{YC_2 - YC_1}{CP_1 - CP_2}$$

$$Energy\ production\ \left[\frac{€}{kWh}\right] = \frac{YC_2 - YC_1}{ED_1 - ED_2}$$

Where:
YC_1 = yearly costs of configuration 1;
YC_2 = yearly costs of configuration 2;
CP_1 = yearly CO_2 production of configuration 1;
CP_2 = yearly CO_2 production of configuration 2;
ED_1 = yearly energy demand of configuration 1;
ED_2 = yearly energy demand of configuration 2.

2.1.2 Sensitivity analysis

A sensitivity analysis was performed in order to investigate how certain factors could influence the obtained results and to which extent. The chosen factors were:

- Energy price;
- Investment costs;
- On site dewatering prior to transport;
- Sludge handling tariffs;
- Transport distance.

The analysis was performed by setting the values for this factor to the ones which would favour the primary sedimentation's case. To obtain a trend with the plant scale, the analysis was performed for both scales (46,000 and 500,000 PE). First, the factors taken individually were explored.

The **energy price**, although the trend in time is a decreasing one, was set to the highest value in Europe (Denmark's energy price is currently 0.2651 €/kWh), as the benefits of primary sedimentation can only increase if the "external energy" price rises. Only the price of the energy used on site was tuned; the one used in the sludge drying facilities was not changed as the energy does not come from the grid.

For the **investment costs**, the costs that make the subtotal direct construction costs into total foreseen costs ("unforeseen costs") were set to 0, so as to reduce the gap between the two configurations even further.

Then the sensitivity analysis focused on the sludge handling related costs. It was assumed that the sludge would be **dewatered on site**, to reduce the costs while enhancing the benefits of primary sludge. The costs of a dewatering facility were not considered. Primary sludge was assumed to reach a 35% dry solids content and secondary sludge 18% (realistic data based on experiments conducted within Waternet: personal communication, Peter Piekema). It was also assumed that the handling costs for dewatered sludge would not change.

Then the **sludge handling costs** were halved, while keeping the same level of profit from biogas and struvite.

Next, the **transport distance** between the WWTP and the sludge handling centre (originally 33 km) was set to 1 km, thus reducing both the CO_2 and the sludge handling costs.

The way the three previous measures help the primary sedimentation's business case is that the total amount of sludge (primary + secondary) from configuration 2 is higher, thus any sludge handling cost reduction will make this configuration cheaper in a higher measure.

Finally, all the above factors were considered at the same time.

A rough calculation (just for the 500,000 PE plant) was performed with a new (lower) **WWF/DWF ratio** (2,1 instead of 2,8). This parameter does indeed change depending on the area, climate, drainage basin etc. (within Waternet's area itself, values ranging from 2 to 3,6 are found). A lower hydraulic load allows for smaller clarifiers and this makes configuration 2, which has a set of primary clarifiers too, cheaper. The calculations related to this sensitivity analysis are more imprecise and are just an indication (costs were all scaled up from the basis situation, thus underestimated, and so were the amounts of concrete).

Moreover, a "backwards" sensitivity analysis on what the price of the primary sedimentation facilities should be in order for primary sedimentation to be convenient was performed. This was obtained through trial and error.

2.1.3 Solar panels & wind energy

The data about the costs of solar panels without subsidies were withdrawn from Waternet's business cases and Table 2.6 gives an overview. The unit with which solar parks are dimensioned is the installed power, expressed in kWp (kilo watt peak). This indicates the power yield of the panels under ideal conditions. It was assumed that, between the two configurations of solar panels possible (V shaped or facing south), the one which has the solar panels facing South (higher power yield but more space) would be chosen (Figure 2.1).

Figure 2.1: V-shaped (left) and South-facing (right) solar panels.

The data about solar panels' costs with subsidies and wind energy were sourced from the "Eindadvies basisbedragen SDE+ 2017" published by ECN (Energieonderzoek Centrum Nederland), the Dutch energy research centre (Lensink & Cleijne, 2016).

The option of renewable energy without subsidies has been considered as there is a possibility that the subsidies will be withdrawn in the future.

An important aspect to take into account when considering the wind energy option, is that there are legal and practical limitations to the constructions of wind turbines in North Holland. In fact, in order to build a new on-land wind turbine, two old ones need to be dismissed and a new wind park needs to have at least 6 wind turbines (Provincie Noord-Holland, 2016).

Within Waternet, it is common practice for LCA calculations to consider the carbon footprint for solar panels to be zero. This means that the CO_2 reduction connected to the production of 1kWh is calculated as an avoided emission caused by the use of grey (fossil fuels) energy, thus 0.67 $kgCO_2/kWh$. In reality, the materials and production of solar panels do have a carbon footprint, and from Nugent & Sovacool, (2014)

it is retrieved that the average CO_2 footprint of solar panels is 0.0499 $kgCO_2/kWh$ produced. Therefore, the actual CO_2 reduction allowed for by solar panels is 0.67- 0.0499 = 0.6215 $kgCO_2/kWh$.
However, in order to be consistent with Waternet's method and since their CO_2 footprint is only 7% of the one of grey energy (and does not impact the study's outcomes), in this study the solar panels were considered to be CO_2 free.

Table 2.6. Cost and characteristics of solar panels facing South (costs excluding VAT).

Parameter	Value	Unit of measure
Price	1000	€/kWp
Power production (100% efficiency)	950	kWh/kWp/y
Ground area occupied	10	m^2/kWp
Maintenance costs	10	€/kWp/y
Lifespan	25	y
Cost of capital	3.50%	
Degradation of power production (efficiency)	0%	in year 1
	10%	in year 10
	20%	in year 25

Table 2.7 gives an overview of the price rates for energy and sustainability for the alternative sources of renewable energy.

Table 2.7. Overview of the energy and sustainability price rates for solar and wind energy.

Wind energy			With VAT
Price of energy production (no subsidies)	€/kWh	0.075	0.091
Price of energy production (with subsidies)	€/kWh	0.028	0.034
Price per CO_2 reduction (no subsidies)	€/$kgCO_2$	0.112	0.135
Price per CO_2 reduction (with subsidies)	€/$kgCO_2$	0.042	0.050

Solar energy			With VAT
Price of energy production (no subsidies)	€/kWh	0.080	0.097
Price of energy production (with subsidies)	€/kWh	0.033	0.040
Price per CO_2 reduction (no subsidies)	€/$kgCO_2$	0.119	0.144
Price per CO_2 reduction (with subsidies)	€/$kgCO_2$	0.049	0.059

2.2 Second research question: sludge and energy recovery

The assessment of the GWP potential of different routes of treatment called for the comparison of different scenarios, with the calculation of primary energy and CO_2 emission balances; short-cycle CO_2 emissions are not considered. The bigger picture is a comparison between a scenario with direct drying and incineration, and one with AD before these processes. However, since the upstream treatment is independent from the results of this study, two "maxi scenarios" were identified: one with both primary and secondary sludge, and one with secondary sludge only.
For each of the scenarios, primary energy and CO_2 emissions saved through the substitution of sources of energy (coal, electricity, heat) were calculated and then compared.

What is of interest for this study are not the carbon footprints and primary energy balances of each single scenario but rather the differences between them. For this reason, some contributions that do not differ much from scenario to scenario were disregarded (i.e. construction materials of the facilities).

A calculation additional to that of primary energy and CO_2 footprint differences was one aimed at assessing the energetic efficiency of the scenarios. Each scenario was regarded as a machine, with energetic inputs (biochemical energy of the sludge, external energy inputs) and outputs (dried sludge, potential electrical energy).

2.2.1 Scenario description

The sludge of this study is assumed to derive from the same type of plant analysed for the first research question (500,000 PE, UCT system with biological removal of phosphorus). It can be of two types: primary + secondary (mixed) or secondary only. As mentioned, the amounts of dry solids and the percentage of organic solids changes if only secondary or both primary and secondary sludge are produced.

In all the scenarios, the incoming sludge is thickened and the thickening step is therefore left out of the control volume. When sludge needs to be digested, it always need to be thickened. When it does not, it can be directly dewatered in a machine called filter press, which uses overall less energy and less polyelectrolytes. However, a lower dry solids percentage can be reached and after the comparison between a configuration with belt thickening plus centrifuge and one with filter press only, it emerged that a belt thickening step is always convenient (energy wise and CO_2 emissions wise).

Whenever AD is present, a direct CH_4 emission to the atmosphere is considered, the quantity of which is proportional to the production.

Moreover, when digestion is implemented, the centrate (the water separated during the dewatering step) has a high nitrogen concentration which requires energy to be removed. This flow can either be sent to the head of the plant and treated with the influent, or a dedicated treatment for ammonia removal can be allocated before the centrate is recirculated. In this study, for simplicity, a dedicated Sharon-Anammox reactor has been considered to take into account the additional energy needed.

When phosphorus is removed biologically, it is bound to the waste activated sludge. However, when the latter is digested, the phosphorus is released and can scale in pumps and pipes creating operational problems. It therefore needs to be removed, and in this study the addition of magnesium chloride is assumed, which forms struvite and binds the phosphorus again. Some of the struvite formed is normally collected in a dedicated reactor (like it happens, for instance, in Amsterdam West). However, no phosphorus recovery has been considered as the quantity only depends on the population equivalents of the plant, which does not change from scenario to scenario.

In all cases there is, as an energy output, dried sludge used as a biofuel that is considered to substitute coal in cement kilns. This biofuel has different calorific content depending on the original composition of the sludge and on the processes. In those scenarios where anaerobic digestion is implemented, an additional energy output is represented by biogas and subsequent electricity and heat generation with CHP.

Since the dried sludge needs to be transported to the cement factory and amount of sludge leaving the plant changes from scenario to scenario, the energy and CO_2 related to transport was considered.

Figure 2.2 gives a schematic overview of the scenarios analysed.

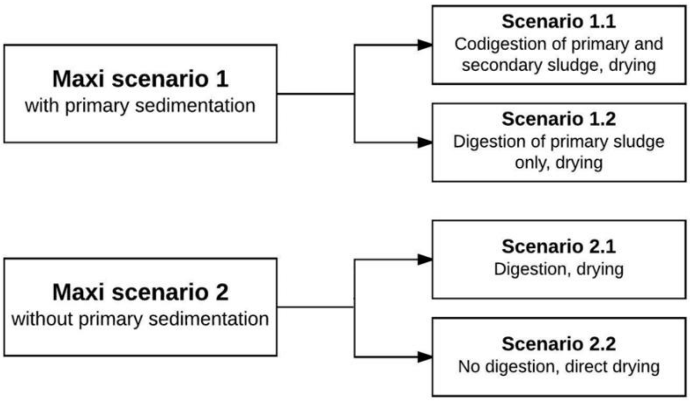


Figure 2.2: Overview of the scenarios.

In the following, the scenarios are visualised (Figures 2.3 – 2.6) and described. Only the arrows representing flows taken into account are shown. The ones not shown (i.e. the condensate from the dryer, the treatment of which is negligible) are related to flows that were neglected.

Scenario 1.1. This scenario represents the current base case scenario, except for the drying step. Normally, the dewatered digested sludge (with a dry solids concentration of about 22%) is directly incinerated, and from this incineration little or no useful energy is recovered. In scenario 1.1, a dryer is introduced which, through the use of heat, brings the dewatered sludge to a solids concentration of 90%. The heat is assumed to derive from an incinerator like the one in AEB. Retrieving this heat entails a "missed" electricity production by the incinerator. This is because this heat is not exactly waste heat. In an ideal situation that would be the case and no "missed" electricity production would be considered. The dryer requires electrical energy too, and it includes the exhaust air treatment, the energy for which is proportional to the amount of water evaporated.

The biofuel produced in this scenario will be the one with the lowest calorific content, and the biogas production will be the maximum one among the scenarios with AD.

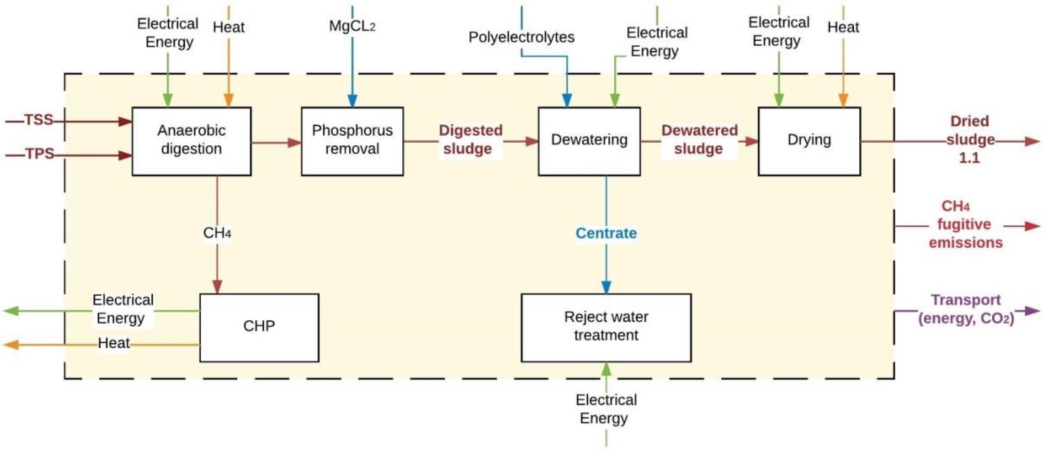


Figure 2.3: Scenario 1.1.

Scenario 1.2. In this scenario, secondary sludge is dewatered without being digested whereas primary sludge goes through digestion and subsequent dewatering. In this case, there is no phosphorus removal as it is still bound to the secondary sludge.

The dried sludge exiting this treatment train will have a higher LHV (Lower Heating Value) compared to the one from scenario 1.1 but the methane production will be lower. The methane fugitive emissions will also be lower, as they are considered to be proportional to the biogas production.

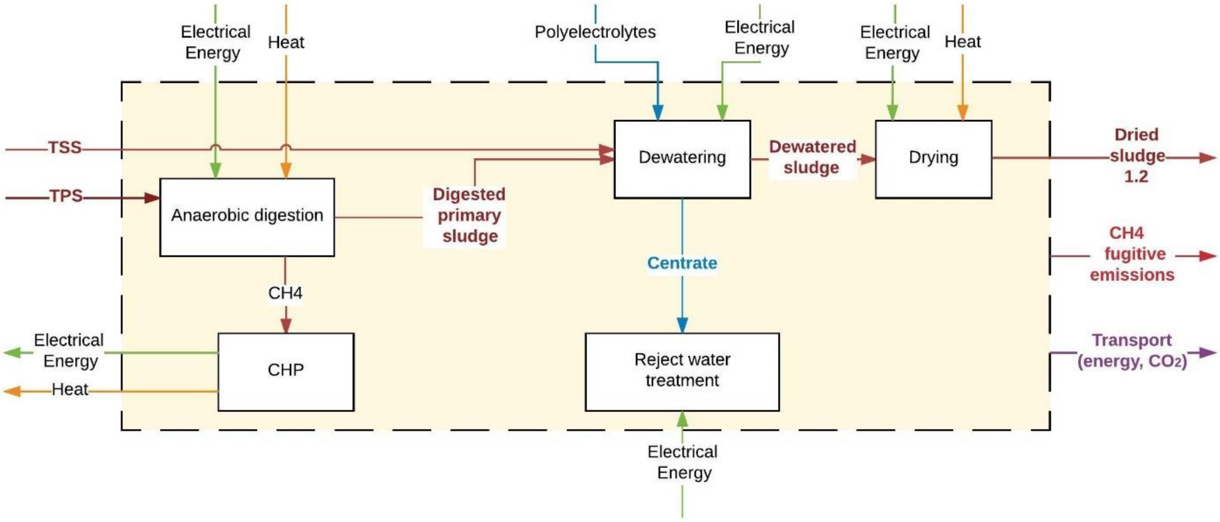


Figure 2.4: Scenario 1.2

Scenario 2.1. As no primary sedimentation is implemented upstream, the sludge entering scenario 2.1 is only secondary sludge. The quantity of dry solids is slightly lower than the sum of primary and secondary sludge in the previous scenarios. The sludge is thickened, digested and the released phosphorus is bound to the sludge through the addition of magnesium chloride.

The biogas production will be higher than the previous scenario but lower than the base case, as secondary sludge has a lower yield.

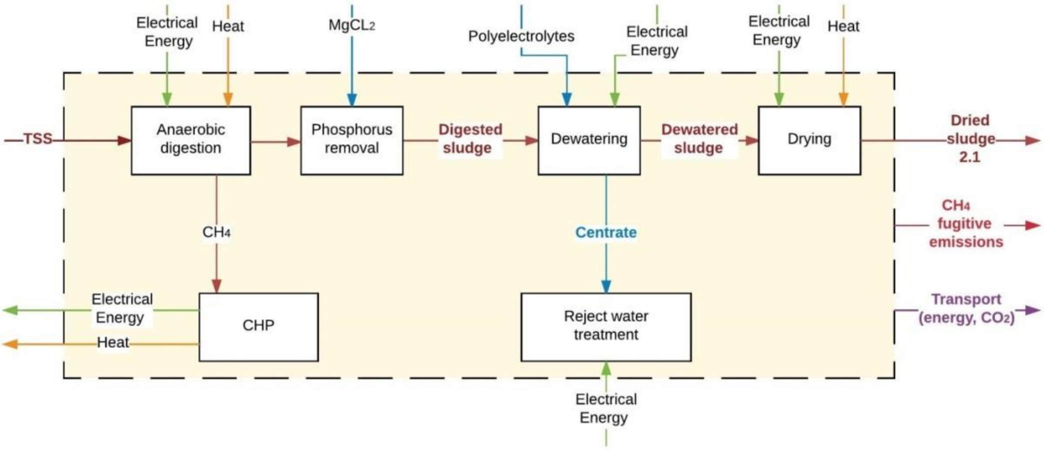


Figure 2.5: Scenario 2.1.

Scenario 2.2. In this scenario, secondary sludge is directly dewatered and dried. The treatment train is the simplest of all; since AD is not implemented, facilities like the digester, the CHP engine and the Anammox reactor are not present.

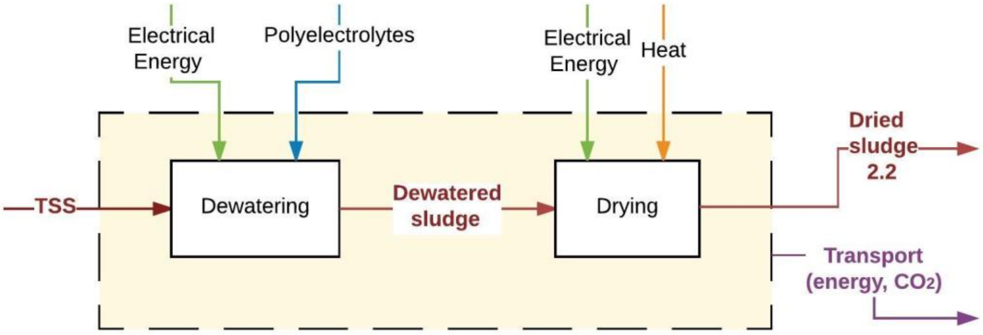


Figure 2.6: Scenario 2.2.

Since all the volatile solids stay in the sludge, the biofuel is the one with the highest calorific value among the four; no other energy is produced.

2.2.2. Data

Table 2.8 shows the sludge quantities, characteristics, and sources of the data. Given the nature of the sludge, which makes it highly dependent on local conditions and type of treatment, whenever possible the data were sourced from the operational logs within Waternet, and some assumptions were made based on the opinion of the experts within the company. When no other source was available, literature data were used. For some data that were not available in literature or within Waternet's operational parameters, some reasonable assumptions were made. Some data regarding the sludge are slightly different than the ones used for the first research question. This is due to the fact that continuity needed to be given with the calculations made for the smaller size plant. The data that were used were relative to the present situation in Amsterdam West; for the analysis of these scenarios instead, a "green field" situation (where the plant would be built from scratch) was imagined and data that for Amsterdam West differ greatly from what is expected, a "normal" Dutch value was used. This was retrieved from the Waterboards' Union website (Unie van Waterschappen, n.d.).

Table 2.8. Basic assumptions.

			Source
Primary sludge (bio only)	5,304	tonds/y	
Chemical sludge	278	tonds/y	
Secondary sludge (with primary sedimentation)	5,352	tonds/y	
Secondary sludge (without primary sedimentation)	9,327	tonds/y	
SS:PS ratio (with primary sedimentation)	~1	-	
Dry solids concentrations			

Thickened SS	6	%	Op. parameter
Thickened PS	4.5	%	Op. parameter
Mixed digested dewatered sludge	23.3	%	Avg. of the waterboards
PS digested dewatered	25	%	Assumption
SS digested dewatered	21	%	Assumption
SS undigested dewatered	20	%	Op. Parameter
Dried sludge	90	%	Op. parameter
Inorganic fractions			
PS	20	%	Op. parameter
SS	25	%	Op. parameter
Solids reduction during digestion			
PS	45	% of total dry solids	Op. parameter
SS	25	% of total dry solids	Op. parameter
Biogas			
Production potential (PS)	1000	Nm^3/tonVS destroyed	Op. parameter
Production potential (SS)	700	Nm^3/tonVS destroyed	Op. parameter
Methane content	65	%	Metcalf & Eddy (2003)
Energy content of methane	0.0364	GJ/Nm^3	
Methane leakages percentage	0	%	
CHP			
Electrical efficiency	37	%	Op. parameter
Heat recovery efficiency	45	%	Op. parameter
Energy and heating requirements			
Heat requirement to evaporate moisture (dryer)	3.24	GJ/tonH$_2$O	Op. parameter (Huber belt dryer)
Electrical energy requirement (dryer)	0.0596	MWh/tonH$_2$O	Op. parameter (Huber belt dryer)
AD heating requirement (average)	0.07759	GJ/m^3 liquid sludge	Metcalf & Eddy (2003)
Energy use for dewatering	89	kWh/tonds	Op. parameter
Electrical energy for Sharon-Anammox	0.4	kWh/kgN$_{in}$	Hauck, Maalcke-Luesken, Jetten, & Huijbregts, 2016
Nitrogen content in sludge (for N concentr. In centrate)			
N content in PS	1.5	% (w/w)	Op. parameter
N content in SS (with primary sed.)	6	% (w/w)	Op. parameter
N content in SS (no primary sed.)	5	% (w/w)	Op. parameter
PE use			
Digested mixed sludge	14	kgPE/tonds	Avg. of waterboards
SS undigested	15	kgPE/tonds	Assumption

PS digested	10	kgPE/tonds	Assumption
SS digested	14	kgPE/tonds	Assumption
Biofuel characteristics			
Energy content of volatile solids	21.662	GJ/tonVS	Stowa (2010)
Heat requirement to evaporate moisture	3.2	GJ/tonH_2O	Stowa (2010)
Gross energy requirements (GER)			
Electricity	11.3	GJ/MWh	RVO, 2017
LHV of substitution coal	24.5	GJ/ton	Senter Novem (2007)
GER of substitution coal	32.6	GJ/kg	RVO, 2017
Primary energy for transport	0.00226	GJ/ton/km	Stowa (2012)
Gross energy requirement of MgCl2 (28%)	$0.924*10^{-3}$	GJ/ton$MgCl_2$ solution	Stowa (2012)
Gross energy requirement of polyelectrolytes	0.133	GJ/kg-activePE	Stowa (2012)
CO_2 emission factors			
Transport	0.11	kgCO_2/ton/km	www.co2emissiefactoren.nl
Substitution coal	2,339	kgCO_2/ton	www.co2emissiefactoren.nl
"Grey" electricity	0.67	kgCO_2/kWh	Stowa (2011)[b]
Magnesium chloride (28%)	0.035	kgCO_2/kg$MgCl_2$ solution	Personal communication, Enna Klaversma
Directly emitted methane	25	kgCO_2/kgCH_4	IPCC (2007)
Polyelectrolytes	2.13	kgCO_2/kg-activePE	Personal communication, Enna Klaversma
Transport distance	304	km	Amst-Antoing
Electricity losses in AEB	0.2	$MWh_{electricity}/MWh_{heat}$	Op. parameter
Solids capture	100	%	Assumption

2.2.2.1 Specifications about the data and sensitivity

Methane leakages. Methane leakages always occur in WWTPs, and in particular in those implementing AD; one of the main contributors is the digested sludge buffer (Daelman et al., 2012; Oshita et al., 2014). This is true also in Waternet's experience, where the buffer is the highest source of fugitive methane. In fact, in 2011 it was found that 60% of the CH_4 emissions from the lava filters (which treat the air coming from all processes except for the biological reactor) originated in the buffer (de Graaff, Zandvoort, Janse, Frijns, & Roest, 2011). This happens because for the nature of the reactors that are the digesters (operated in parallel); the average residence time is around 20 days but some of the sludge leaves the digester sooner. When it gets to the buffer, the microorganisms still digest it and the air rich of methane above the sludge in the buffer is simply released to the atmosphere. However, the methane leakages can and should be brought close to zero via measures such as using the buffer as a successive digester (in series). This way, the air rich in methane from the buffer is also sent to the CHP achieving both an emission reduction, and an additional energy recovery. Moreover, Hjort-Gregersen (2014) conducted a study about methane emissions from biogas plants and he found a range of percentage of 0-10%. For this reason, in this study the methane slip was first considered to be 0% (therefore assuming a state-of-the-art biogas plant) and then, in the sensitivity, the aforementioned range was explored.

Dry solids concentrations and polyelectrolytes use in dewatering. One of the processes for which data were more uncertain is dewatering. Since it is common practice to dewater primary and secondary sludge together after digestion, no data were found on separately digested sludge about polyelectrolytes use and dry solids percentages achieved. In a personal communication with Kees Roest, a researcher for KWR Watercycle Research Institute who carried out a study about the predictability of sludge dewatering performances from lab tests, it emerged that such tests are indeed unreliable. Therefore, the unknown data about dewatering had to be assumed. For raw (undigested) sludge, experiments had previously been carried out and data were available. From here, assumptions were made bearing in mind that digestion improves secondary sludge's dewaterability (bringing it to a percentage higher than 18%) and worsens primary sludge's (lowering the 35% of the raw PS). The same line of thought was used for polyelectrolytes dosage. In fact, the ranges found in literature for this parameter are very large and different from source to source.

In order to assess the impact of the dewatering dry solids percentage achieved on the whole system, a sensitivity analysis was performed. The dry solids concentrations of digested PS and digested SS only were increased, since they are the most uncertain parameters, to avoid underestimations. The dry solids concentration of digested SS was increased by 2%. To the author's best knowledge, there is no reason to believe that digested SS would be dewatered to a higher concentration than mixed digested sludge. The concentration of digested PS was increased by 5%. Again, the same principle was applied to the polyelectrolytes dosage; the unknown values (relative to PS or SS dewatered separately) were tuned.

Evaporation heat. This parameter determines the energy needed to evaporate the moisture content of the sludge during drying. The tabulated value for water is 2.256 GJ/tonH_2O. However, more energy is needed to evaporate water from sludge: for a Huber belt dryer (Huber SE, 2017) the specific thermal energy is around 0.9 kWh/kgH_2O (corresponding to ~3.24 GJ/tonH_2O). ECN too, in one of its reports from 2009 (van Doorn & van de Kamp, 2009), state that the value is 3.2 GJ/tonH_2O. For the base calculation, the value of 3.24 GJ/tonH_2O was chosen. Another manufacturer, Komline-Sanderson (Komline-Sanderson, n.d.) claims an energy requirement for drying of 1,155 BTU/lbH_2O (~2.7 GJ/tonH_2O). This value has thus been used in the sensitivity analysis.

Biogas production potential. The values used in the base calculation (1,000 and 700 Nm^3/tonVS destroyed for PS and SS respectively) were retrieved from Waternet's logs. However, both in literature and in a report from STOWA ("Stichting Toegepast Onderzoek WAterbeheer") different values can be found. In the report, (STOWA, 2011)[a] it is stated that the specific biogas production is 800 and 600 Nm^3/tonVS for PS and SS respectively. Thus, the base values used were the ones from Waternet, then the ones from STOWA were explored in the sensitivity analysis, together with an increase of 10% (from Waternet'numbers). Figure 2.7, adapted from the same STOWA report, offers a simple visualisation of the principles behind sludge digestion.

Methane content. According to Metcalf & Eddy (2003), 65% of the biogas is methane. However, this percentage can vary; according to STOWA (2011)[a] the range is 58-73%. This factor was explored in the sensitivity analysis.

Growing SS:PS ratio. The ratio of secondary and primary sludge (close to 1) used for the base case calculations is relative to a normal WWTP. However, some sludge treatment facilities (like Amsterdam West's) treat sludge from several WWTPs (which not always implement primary sedimentation), and this ratio can increase. Therefore, the amount of secondary sludge was increased in a sensitivity calculation to see how this affects the comparison between scenarios 1.1 and 1.2.

Solids capture. The mechanical processes that separate solids and liquid have a certain capture rate, lower than 100%, thus some of the solids "escape" the treatment. This means that the actual sludge that reaches the final stage is lower (and so is the energy recovered from it). However, the percentages are very high (according to Andreoli, von Sperling, Fernandes & Ronteltap, (2007), around 90-98% for dewatering) and the reject water is indeed sent back to the headworks. The actual amount of solids escaping the treatment should therefore be calculated through iteration but the quantity is low enough to be neglected. Therefore in the calculations the solids capture was considered to be 100%.

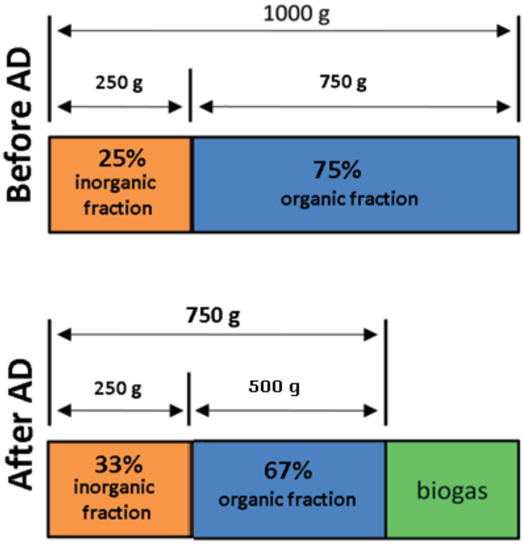


Figure 2.7: Schematisation of the basic principle behind sludge AD (percentages related to SS).

Transport. The transport distance used in the calculations is the one between Amsterdam West and Antoing, a Belgian city hosting a cement factory (Cimenteries CBR). However, this transport distance could vary depending on the recipient of the dried sludge; therefore this factor has been explored (tuning it between 304 km and 0 km) through the sensitivity analysis.

Drying heat type. In the basic situation, which stems from what would happen in Amsterdam West, the heat used to dry the sludge comes from the AEB incinerator. However, it is not truly waste heat, as its withdrawal entails a "missed electricity production". For this reason, a (ideal) situation in which the heat is actually waste heat was explored too in the sensitivity analysis.

Substitution values for coal. In the usual calculations for the MJA ("Meerjarenafspraken"), the substitutions relative to primary energy carriers (i.e. coal) are done using the calorific value. That is, the energy content of the coal is considered as the primary energy requirement. However, when assessing the environmental impact of substituting dried sludge to coal, two values should be considered. One is the calorific value of the coal that needs to be substituted, which determines the yearly quantity of traditional coal saved. The other is the Gross Energy Requirement (GER) of coal. The GER value is defined as a measure of the gross energy content of a substance expressed in primary energy; it gives an estimation of the primary energy required to produce fuels, chemicals, etc. including the calorific value of the product itself. This last value determines how much primary energy is saved by saving 1 kg of coal. This value will be higher than the mere calorific value of the coal because all fuels need energy to be refined, transported etc. For these reasons, in this study the GER value of the substitution coal (namely hard coal briquettes) was used to assess the impact on primary energy savings.

Primary energy factor (PEF) for electricity. The primary energy factor is a measure that takes into account the primary energy consumption different energy carriers; it keeps track of the primary energy lost in the transformation. It is analogue to the GER value for electricity. The conversion factor normally used to retrieve the PEF for electricity is 2.5 GJ_{prim}/GJ_{sec} (for EU, based on an average coal fired plant efficiency of 40%). This means that in average, to produce 1 GJ of secondary energy (electricity), 2.5 GJ of primary energy (i.e. coal) are needed. This corresponds to 9 GJ/MWh. However, as stated in a report from the International Institute for Sustainability Analysis and Strategy (Fritsche & Greß, 2015), the PEF is due to decrease with the increasing share of renewable sources in the energy mix. Actually, in a ISI (Institut für System- und Innovationsforschung) report, Esser & Sensfuss (2016) stated that the 2.5 factor is already inadequate, and calculated a new factor with different methods (Table 2.8).

Table 2.8. Calculated PEF of electricity (Esser et al., 2016).

Method	2000	2005	2010	2015	2020	2025	2030
Method 1	2.41	2.37	2.26	2.08	1.87	1.79	1.74
Method 2	2.41	2.36	2.14	1.90	1.59	1.46	1.35
Method 3	2.52	2.49	2.38	2.21	2.01	1.93	1.87
Method 4	2.65	2.61	2.49	2.30	2.09	2.00	1.93

In the calculations for the MJA, Waternet uses the 9 GJ/MWh factor. However, the same line of reasoning adopted for the substitution coal can be assumed here. The 2.5 GJ/GJ value is only based on the efficiency of the coal plant, but the burnt coal has itself a GER, since it needs to be extracted, refined and transported. The "GER-waarden en CO_2 lijst" published by "Rijksdienst voor Ondernemend Nederland" (RVO, 2017), indeed attributes to the electricity in the Netherlands a GER value of 11.3 MJ/kWh (corresponding to 3.14 GJ/GJ). It is not clear whether this value takes into account the losses in the process, but it seems to reflect better the primary energy requirements of the process. For this reason, this new value was used for the base calculations; then, the PEF was decreased until 1 GJ/GJ.

CO_2 footprint of electricity production. As mentioned, the factor used to convert electricity use to CO_2 equivalents was 0.67 kgCO_2/kWh, which is relative to "grey" electricity. However, the average carbon footprint for the Dutch energy mix is lower than that. Based on the report from ECN (Gerdes, 2013), the factor for 2020 is 0.43 kgCO_2/kWh. Therefore, the factor has been tuned to explore the change in CO_2 reduction potentials of the scenarios.

Finally, in order to determine quantitatively which of the factors the results were most sensitive to, the differences in performances were calculated for the factors set to the two extremes of their own range. Then, a difference between these two values was determined; the higher this number, the more sensitive the results are to the factor. The ranges used for each factor are the realistic ones in which the factors are reasonably expected to change. For instance, the PEF is expected to decrease according to the changes in the energy mix but not to increase; the same goes for the CO_2 footprint of electricity production. Table 2.9 shows the ranges used for the sensitivity factors in these calculations.

Table 2.9. Ranges of values attributed to factors for the sensitivity analysis.

Factor	Range	Unit of measure
PEF	11.3 – 9	GJ/MWh
Transport distance	304 – 0	km
Methane leakages	0 – 10	%
Polyelectrolytes use	-4 – +4 (from base calculations)	kgPE/tonds
Evaporation heat	3.2 – 2.7	GJ/tonH_20
Specific biogas production	SS: 600 – 770 PS: 800 – 1100	Nm^3/tonVS destroyed
Methane content in biogas	58 – 73	%
Drying heat type	AEB heat – Waste heat	-
CO_2 footprint of electricity	0.67 – 0.43	kgCO_2/kWh
Dewatering sludge ds concentrations (for digested PS and digested SS alone)	PS: 25 – 30 SS: 21 - 23	%

3. Results and discussion

3.1 First research question: primary sedimentation

3.1.1 Plant size analysis

From the plant size analysis, performed for 500,000 PE, with standard prices and costs and maximum unforeseen costs, it emerged that the price per kWh of energy saved (or, better, produced) with primary sedimentation is around 0.55 €/kWh. This makes primary sedimentation a very expensive energy production technology, if we consider that the price of energy from the grid is currently 0.10 €/kWh. The price per kilo of carbon dioxide reduced is 0.92 €/kgCO$_2$. When this is compared with the CO$_2$ reduction allowed for by solar panels, for instance, it is still a very high value. In fact, using solar energy (which is at the moment of writing subsidised) allows us for a price rate of 0.040 €/kWh which yields a 0.059 €/kgCO$_2$-reduced (values including VAT). Even in the case scenario in which solar panels are not subsidised, they would still be much cheaper; in fact, the price rates in that case would be 0.097 €/kWh and 0.144 €/kgCO$_2$-spared. Figures 3.1 and 3.2 offer a visualisation of the results. The values for the small size (46,000 PE) were also included.

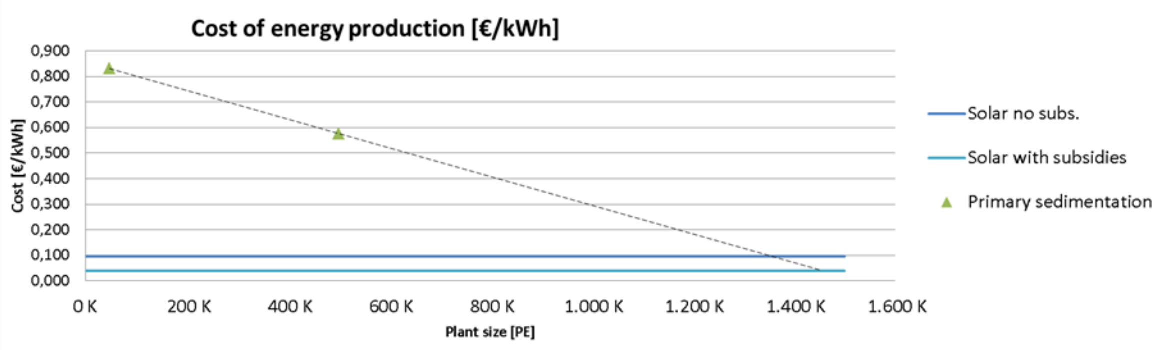


Figure 3.1: Graph with the cost of energy production for the different technologies.

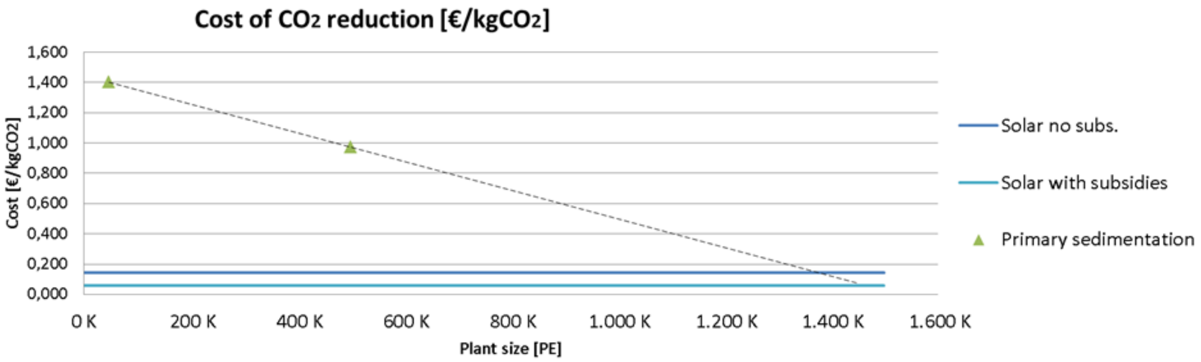


Figure 3.2: Graph with the cost of CO$_2$ reduction for the different technologies.

As visible from the graphs above, the cost rates did decrease with the plant size. For 46,000 PE, they were 0.83 €/kWh and 1.40 €/kgCO$_2$.
Thus primary sedimentation does become more convenient when the size of the plant increases. However, the rate of decrease is not high enough for it to become convenient at a relevant size for the current

situation in Waternet. In fact, if the scenario for which the trend is linearly decreasing is considered (which is a favourable scenario for the primary sedimentation's business case), and the intersection point between the cost rate for primary sedimentation and, for instance the cost of solar panels without subsidies is found, the correspondent scale for this intersection point is around 1.4 mil PE. In current times, this is a scale bigger than the ones considered by Waternet. However, as it will be explained in the discussion paragraph, the trend is not linear but exponentially decreasing.

Table 3.1 gives an overview of yearly costs and investment costs differences between the two configurations.

Table 3.1. Overview of cost, energy and CO_2 differences between the two configurations.

Aspect	Unit of measure	Value
Additional investment costs	€	18,247,000
Additional yearly costs	€	2,566,000
Delta energy use	kWh/y	4,686,000
Delta CO_2 production	$kgCO_2/y$	2,781,000
Euros per kWh saved	€/kWh	**0.55**
Euros per $kgCO_2$ saved	€/$kgCO_2$	**0.92**

At the present state of things, it is therefore much cheaper to use solar panels instead.

To meet the energy use difference between the two configurations (~4,700 MWh/y), a solar panels installation of 5,542 kWp would be needed. This would cost, without subsidies, around 6,7 mil€ (incl. VAT). This is much cheaper than the 18 mil€ needed for the primary clarification facilities. In terms of ground area needed, a solar panels field of that capacity would occupy around 55,500 m^2. In those WWTPs where space is limited, there is a possibility to install the solar panels on top of the clarifiers and buffers. However, according to research performed within Waternet, this would drive the costs up by around 45% (personal communication, Gijs van der Meer).
If the additional 18 mil€ needed to invest in primary clarification were invested in solar panels instead, a plant of the capacity of around 15 MWp could be bought; this would produce around 12,500 MWh/y and match a CO_2 offset of around 8,500 $tonCO_2/y$.
To meet the carbon footprint offset between the two configurations (~2,780 $tonCO_2/y$), a solar panel plant of around 5,000 MWp would need to be installed. This would cost just around 6 mil€ (incl. VAT) and it would produce around 4,000 MWh/y. The yearly costs would be around 400,000 €/y (incl. VAT).

3.1.2 Sensitivity analysis

The results of the sensitivity analysis are shown in Table 3.2 and visualised in Figures 3.3 and 3.4.

Table 3.2. Sensitivity analysis (500,000 PE).

Sensitivity	Factors tuned	Price per kWh (€)	Price per $kgCO_2$ (€)
Base case scenario	**-**	**0.55**	**0.92**
Energy	Unitary energy price	0.53	0.89
On site dewatering	Tons of liquid sludge transported/sludge dewatering costs	0.43	0.67
Investment costs	Total foreseen construction costs	0.43	0.73
Sludge handling	Sludge handling costs	0.47	0.79
WWTP-CSI distance	N. of km between WWTP and CSI	0.47	0.74

Best case scenario	*All factors together*	*0.27*	*0.42*
Solar panels no subsidies		0.097	0.144
Wind energy no subsidies		0.091	0.135

As stated already, the factors were tuned to the best possible value that could help making primary sedimentation convenient. In all cases, even for the sensitivity analysis which grouped all the factors together (best case scenario), primary clarification was never convenient.

Figures 3.5 and 3.6 show the trend lines of the data points for the base case scenario and the best case scenario. Again, the linear trend line is only an indication.

In regard to the sensitivity to the WWF, results showed that configuration 2 does indeed get much cheaper (0.38 €/kWh and 0.64 €/kgCO_2) but it is still by measure more expensive than the alternatives. The data on which this calculation was based however are more imprecise.

Figure 3.3: Variation of the cost of energy production and CO_2 reduction for different sensitivity factors.

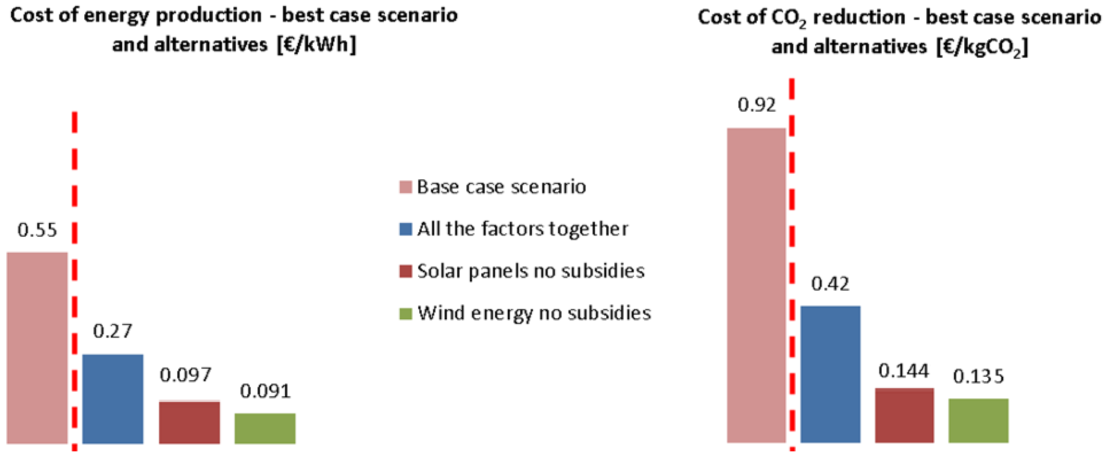


Figure 3.4: Comparison of cost of energy production and CO_2 reduction with best case scenario and alternatives.

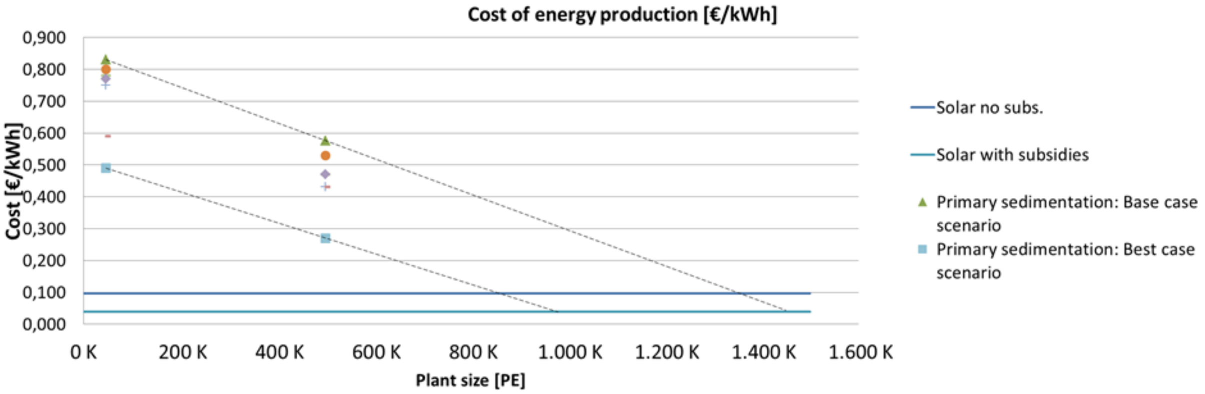


Figure 3.5: Trend lines for base and best case scenarios (energy production cost).

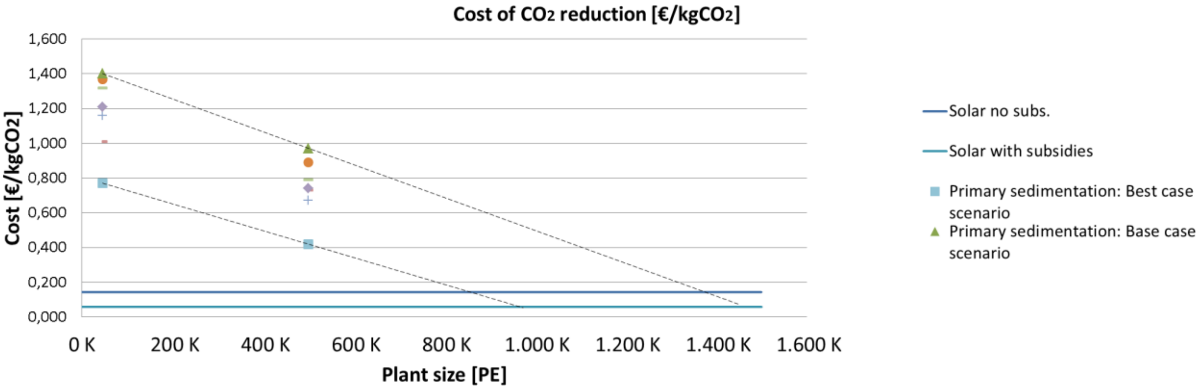


Figure 3.6: Trend lines for base and best case scenarios (CO_2 reduction cost).

From the "backwards" sensitivity analysis It emerged that even if the primary clarifiers, primary sludge recirculation pumps and splitbox cost 0, the configuration would still be too expensive. This is because there are other facilities connected to primary clarification (primary sludge thickeners, for instance) the capital cost of which still drives the yearly costs up. Therefore, not only should the clarifiers and recirculation pumps cost zero, but also, for instance, the primary sludge thickener pumps.

3.1.3 Discussion

An important remark needed for the interpretation of the results is that they are specific for the situation in Weesp and they cannot be taken out of context. The outcome of the calculations will change accordingly with organic and hydraulic loads, characteristics of the sludge, prices etc. Therefore, to answer the research questions for another plant, a thorough cost assessment should be performed. Nonetheless, they do give an indication of the fact that it is fairly likely that primary clarification is now an obsolete process to apply (in terms of energy and CO_2 reduction costs), at least for certain plant sizes. Moreover, the investment costs are estimated, and as such they have a high degree of uncertainty. They are not to be taken as a quote. The base from which they are scaled up was obtained through the use of an SSK sheet (which is already an estimation). The costs of some facilities (see table 2.1) have also been estimated with the SSK and are slightly higher than what they would have been if they were scaled up squared. This means that the other costs were underestimated (they are on the safe side, i.e. the cost of primary sedimentation is on the low side).

Since it was beyond the scope of this study, no other data point were calculated for the costs of energy production and sustainability. However, a trend line, which is not linear, can be hypothesised. In fact, when building a treatment plant, the investment costs vs the plant capacity have an exponentially decreasing trend (Figure 3.7). This means that for small capacities, the economy of scale allows for a very marked cost decrease, whereas at bigger scales the cost per population equivalent is the same. This is due to the fact that at bigger scales, more sedimentators need to be built (because of the constraints on the maximum diameter), therefore the scaling up is not squared anymore but linear. Since the costs of energy production and CO_2 reduction are based on the yearly costs, that are in turn proportional to the investment costs, the trend line is expected to assume the same shape as the one shown in Figure 3.7. Thus, primary sedimentation as a sustainability measure is not expected to ever compete with solar panels.

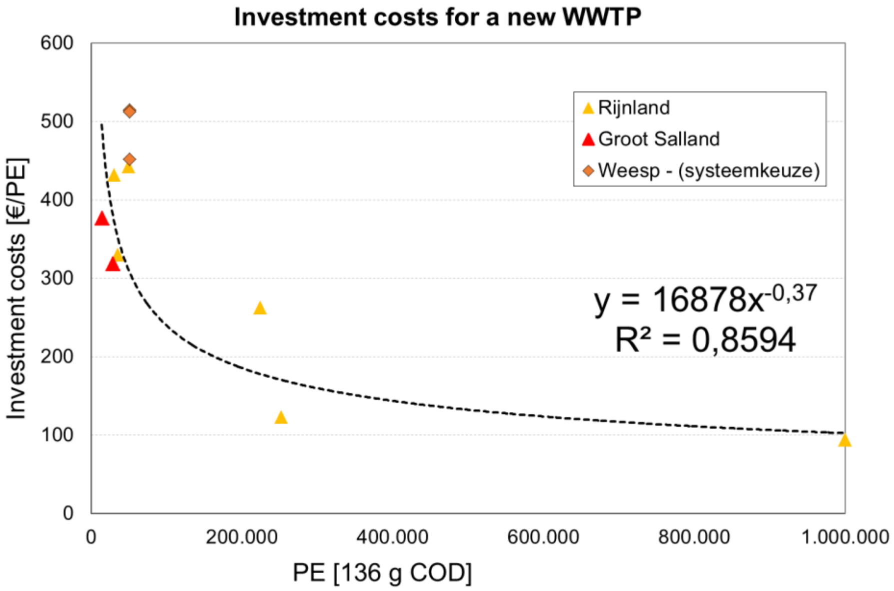


Figure 3.7: Relationship between scale of the plant and investment costs (adapted from Berg, Reitsma, de Vries, Geerse, & van der Velde., 2015).

Following a discussion with a representative from Hollandse Delta (O. Duin) that performed a similar calculation for a 500,000 PE treatment plant, the option of not digesting the secondary sludge in configuration 1 was considered (although it is highly unlikely and unsustainable to not recover any energy from the sludge). The yearly costs difference between the configurations did indeed shrink considerably. However, the additional investment and yearly costs still allow for the installation of a solar panel field which can match and even exceed the energy difference between the two configurations.

Another important remark about the data is that the influent loads have been scaled up using the Weesp situation. Among the dimensioning parameters is the Wet Weather Flow (WWF), which determines the maximum hydraulic load and in turn the size of the sedimentators. As shown in the rough sensitivity calculation, WWF can have a high impact on the financial feasibility of primary sedimentation. This will be even more true in the case of a plant receiving wastewater from a separate sewer system: in this case, the maximum hydraulic load will be the maximum dry weather flow only. Equally, the WWF could be even higher for other regions as could the DWF (per capita water consumption in the Netherlands is 120 l/d, whereas in other countries it is much higher). This is an additional reason to bear in mind the high dependence of the results on the specific situation.

There are two pros to primary sedimentation that have not been considered in this study. One is that an additional function of primary clarifiers is grease removal. For the sake of concreteness, an alternative grease removal facility should have been considered in the configuration without primary sedimentation (a sand trap equipped with grease removal, for instance). The price of this additional facility is however not significant when compared to the total investment costs. An additional benefit connected to primary clarification is that sand can be removed in the sludge line instead of in the water line, by means of a cyclone, which is cheaper than the sand trap in the waterline. However, the savings represent few percentage points of the total investment, which again does not change the fact that configuration 2 would still be too expensive.

Finally, it is important to remember that there is no one-size-fits-all solution; for instance, for a water authority that has no option of matching the carbon dioxide with solar panels or wind turbines, primary sedimentation should still be implemented if CO_2 reduction is the goal.

3.2. Second research question: sludge to energy

3.2.1. Base case scenario

The primary energy saving and CO_2 reduction potentials were calculated for all the scenarios. Scenario 1.1 and Scenario 1.2 were compared (within Maxi scenario 1) and the same was done for scenarios 2.1 and 2.2 (within Maxi scenario 2). The differences between the potentials showed which scenario was more convenient. Again, short-cycle CO_2 emissions were not considered. The results of the base case calculations are shown in table 3.3.

Table 3.3. Results of the energy and CO_2 balances for the base case scenario.

Primary energy savings					
		With primary sedimentation (Maxi scenario 1)			
		1.1 (all sludge digested)	*1.2 (only PS digested)*	*Difference (1.1 - 1.2)*	
GJ saved	*GJ/y*	173,378	148,159	25,219	***1.1 is better***
Energetic efficiency:	%	**49.5**	**50.5**		***1.2 is more efficient***
		Without primary sedimentation (Maxi scenario 2)			
		2.1 (ss is digested)	*2.2 (ss is not digested)*	*Difference (2.1 – 2.2)*	
GJ saved	*GJ/y*	82,850	82,059	791	***2.1 is better***
Energetic efficiency:	%	**41.0**	**50.6**		***2.2 is more efficient***
CO_2 savings					
		With primary sedimentation (Maxi scenario 1)			
		1.1 (all sludge digested)	*1.2 (only PS digested)*	*Difference (1.1 - 1.2)*	
CO_2 saved	*tonCO_2/y*	12,802	11,074	1,008	***1.1 is better***
		Without primary sedimentation (Maxi scenario 2)			
		2.1 (ss is digested)	*2.2 (ss is not digested)*	*Difference (2.1 – 2.2)*	
CO_2 saved	*tonCO_2/y*	6,708	7,564	-856	***2.2 is better***

For the primary energy savings, the scenarios that implement AD to all the sludge (1.1 and 2.1) perform better. However, the differences are minimal. In fact, in the comparison between 1.1 and 1.2 the difference

in savings represents 15% of the average of the saving potentials. In the comparison between 2.1 and 2.2, this percentage is 1%. Therefore, 2.1 at least and 2.2 can be considered equivalent.
However, the energetic efficiencies of the scenarios seen as “machines”, reflect a different situation. In fact, scenarios 1.1 and 1.2 present almost the same efficiency (around 50%), and they do differ in terms of primary energy saving performances. Instead, scenario 2.2 presents a higher energetic efficiency (50.6% against 41%) but the two scenarios perform the same in terms of primary energy savings.
This can be explained by the nature of the primary energy factor. Since normally, to produce 1 MWh of electricity 11.3 GJ of primary energy are necessary, the extra electricity produced via biogas valorisation assumes a weighty role. However, if the factor decreases to a value close to 3.6 GJ/MWh (for instance in a situation where most of the electricity is produced via renewable energy), the primary energy saving performances will tend to reflect the energetic ones.
In terms of CO2 emission reduction, the scenarios show very similar performances. Scenario 1.1 is better than 1.2 (but the difference is around 8.7% of the average of the potentials) and scenario 2.2 is better than 2.1 (with a difference 12% of the average of the potentials).

Figure 3.7 shows the Sankey diagrams of the energy flows that make up the energetic efficiency of the different scenarios.

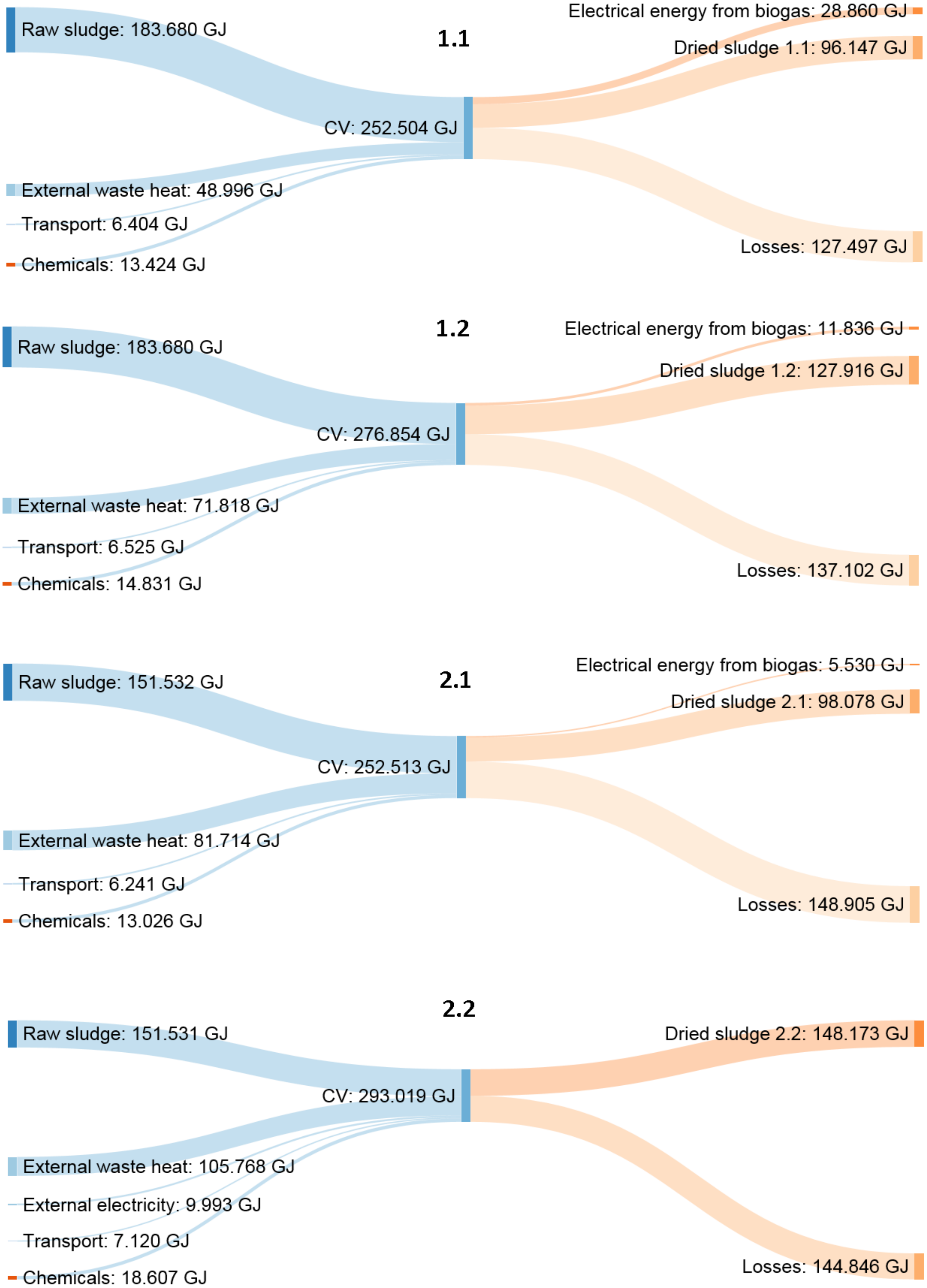


Figure 3.7: Sankey diagrams with the energy flows for all the scenarios (GJ/y); CV = Control Volume.

3.2.2. Sensitivity analysis

For the sensitivity analysis results, only the factors that changed the base case situations are shown graphically. The others, are only briefly discussed.
For simplicity in the visualisation of the results, the following names are given to the scenarios:

- 1.1: PS_{dig} + SS_{dig}
- 1.2: PS_{dig} + SS_{undig}
- 2.1: SS_{dig}
- 2.2: SS_{undig}.

In the tables, in brackets is stated the best scenario.

Methane leakages. In terms of primary energy, although with growing methane leakages percentages scenarios 1.2 and 2.2 gain some advantage against the ones they are compared with, even at a maximum percentage (10%) they still perform worse. Scenario 2.2 as good as 2.1 when the percentage of leaked methane is around 2% (Figure 3.8).
In terms of CO_2 reduction, it is interesting to see the switch at which scenario 1.2 (PS only digested) performs better as good as scenario 1.1 (PS and SS digested): this happens for a methane leakage around 4.5%. As expected, scenario 2.2 increases its performance even more with growing methane slips (Figure 3.9).

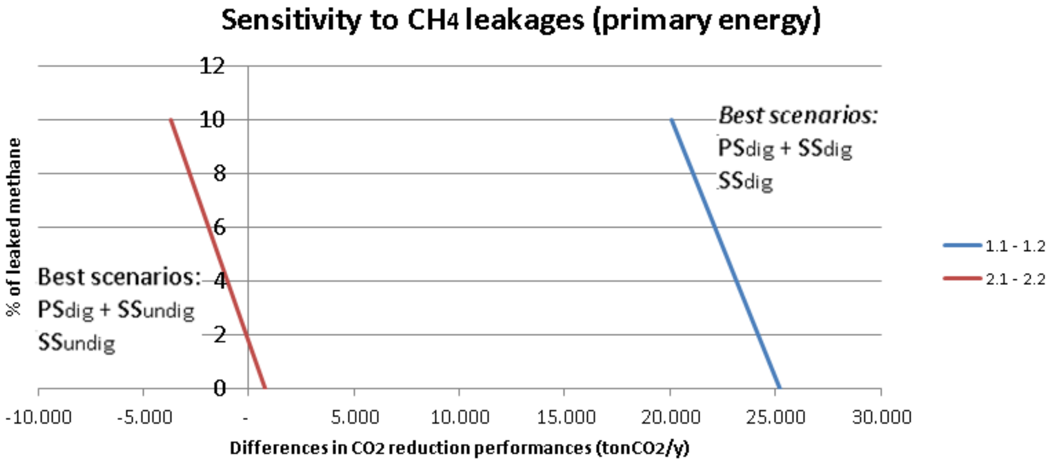


Figure 3.8. Sensitivity of primary energy saving performances to methane leakage.

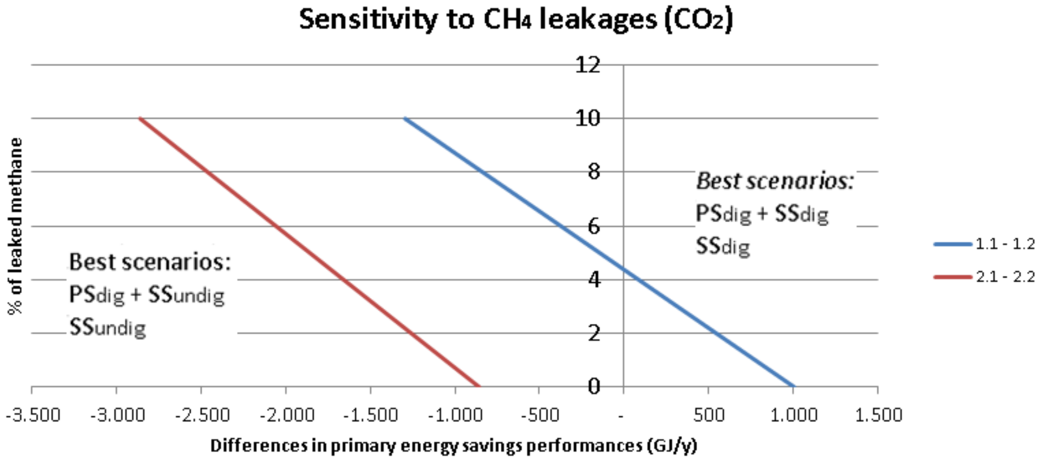


Figure 3.9. Sensitivity of CO_2 reduction performances to methane leakage.

Dewatered sludge dry solids percentage. While in terms of CO_2 performances no meaningful changes were observed, the dewatered sludge dry solids concentration of singularly digested PS and SS had a large impact on primary energy saving performances. This is particularly true for the comparison between scenarios 2.1 and 2.2. The difference between their performances is indeed increased tenfold. This is due to the high sensitivity of scenario 2.1 to the dry solids percentage of digested SS. The results are shown in Table 3.4.

A sensitivity analysis was performed on scenario 2.1 only to find the relation between dewatering performances and primary energy savings. The trend was found to be polynomial (Figure 3.10); in fact, given the exponential nature of the relationship between solids concentration and volume of water in sludge, an increase in percentage in the left part of the curve has a bigger effect than in the right part (Figure 3.10). The same trend was observed for CO_2 savings, which are directly proportional to primary energy savings.

Table 3.4. Comparison of scenarios performances for increased dry solids percentages of digested SS and PS.

	Base situation	Dig. SS ds%: 23; Dig. PS ds%: 30
Primary energy savings		
1.1 – 1.2	25,219 GJ/y (PS_{dig} + SS_{dig})	20,029 GJ/y (PS_{dig} + SS_{dig})
2.1 – 2.2	791 GJ/y (SS_{dig})	9,040 GJ/y (SS_{dig})
CO_2 reduction		
1.1 – 1.2	1,008 tonCO_2/y (PS_{dig} + SS_{dig})	700 tonCO_2/y (PS_{dig} + SS_{dig})
2.1 – 2.2	-856 tonCO_2/y (SS_{undig})	-366 tonCO_2/y (SS_{undig})

Polyelectrolytes use in dewatering. Tuning the polyelectrolytes dosage did not have a significant effect on the CO_2 reduction balances. The same can be said about the comparison for primary energy between scenario 1.1 and 1.2 (PS+SS). However, the primary energy saving difference between the performances of scenarios 2.1 and 2.2 (the ones treating SS only) showed a high sensitivity to the polyelectrolytes dosage required for SS, digested and undigested. First the dosage for SS undigested only was decreased by 4 kgPE/tonds; then the same was done for SS digested only. The biggest change was observed in the second case. The difference between the two performances represented 5.4% of the average of the performances (against an original 1%).

Evaporation heat. Setting the evaporation heat required to 2.7 GJ/tonH_2O did not change the situation significantly.

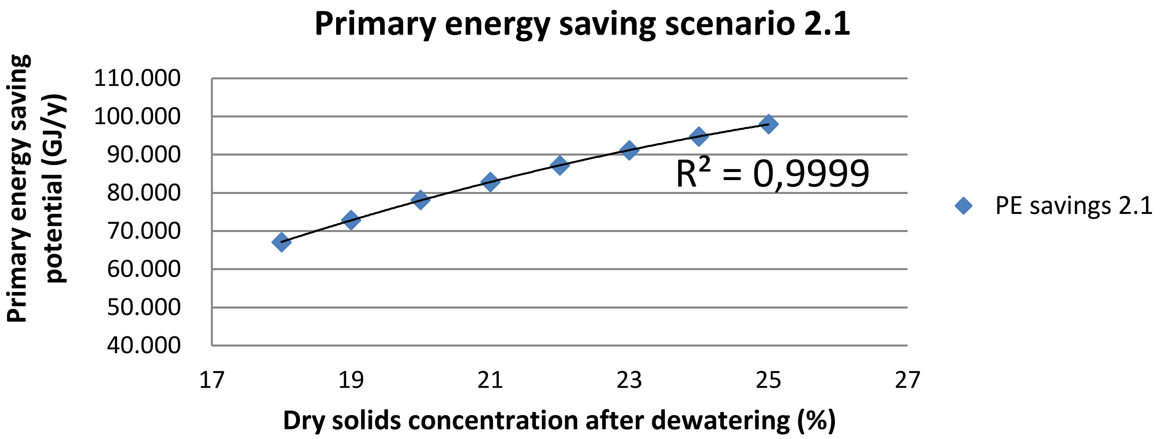


Figure 3.10 Primary energy savings in relation to dewatering performances (Scenario 2.1).

Biogas production potential. When the lower values from STOWA were inserted in the calculations, as expected the scenario less or not at all reliant on AD (1.2 and 2.2) performed better than in the first case scenario, with scenario 2.2 becoming better than 2.1 in terms of primary energy. When the specific biogas production increases to for instance 1,100 and 800 Nm^3/tonVS-destroyed (for PS and SS respectively), the opposite is observed; scenario 2.2 is better than 2.1 in terms of CO2 (by only 525 tonCO_2/y), but the scenario more reliant on AD perform better. The numerical results can be observed in table 3.5.

Table 3.5. . Comparison of scenarios performances for different biogas production potentials.

	Lower biogas production potential	Base situation	Higher biogas production potential
Primary energy savings			
1.1 – 1.2	16,077 GJ/y (PS_{dig} + SS_{dig})	25,219 GJ/y (PS_{dig} + SS_{dig})	31,618 GJ/y (PS_{dig} + SS_{dig})
2.1 – 2.2	-7,175 GJ/y (SS_{undig})	791 GJ/y (SS_{dig})	6,367 GJ/y (SS_{dig})
CO_2 reduction			
1.1 – 1.2	465 tonCO_2/y (PS_{dig} + SS_{dig})	1,008 tonCO_2/y (PS_{dig} + SS_{dig})	1,388 tonCO_2/y (PS_{dig} + SS_{dig})
2.1 – 2.2	-1,329 tonCO_2/y (SS_{undig})	-856 tonCO_2/y (SS_{undig})	-525 tonCO_2/y (SS_{undig})

Biogas composition. As expected, a higher methane content in biogas favoured scenarios 1.1 and 2.1. The values were affected in the same measure as for the previous factor (biogas production potential).
Growing SS:PS ratio. The amount of secondary sludge for the maxi scenario 1 was doubled; the difference in primary energy savings between 1.1 and 1.2 doubled, making 1.1 ever more convenient. The difference in CO_2 saving potential tripled.
Transport distance. Tuning this factor, given its low weight in the energy balance, did not produce any meaningful in terms of primary energy performances of the scenarios, even when switched to zero. The same can be said for the CO_2 reduction performances. However, this factor affected the comparison between 2.1 and 2.2 more than it did the comparison between 1.1 and 1.2. This is coherent with the fact that the differences in dried sludge production for the comparison 2.1-2.2 is ten times that of the comparison 1.1 -1.2.
Drying heat type. When the heat used for drying is waste heat, scenario 2.2 performs much better both in terms of primary energy (becoming better than 2.1) and CO_2 savings. However, scenario 1.1 still performs

better in both regards (although the advantage shrank considerably). Table 3.6 compares the two situations.

Table 3.6. Comparison of scenarios performances for AEB heat and waste heat use.

	Heat from AEB	Waste heat
Primary energy savings		
1.1 – 1.2	25,219 GJ/y (PS$_{dig}$ + SS$_{dig}$)	10,892 GJ/y (PS$_{dig}$ + SS$_{dig}$)
2.1 – 2.2	791 GJ/y (SS$_{dig}$)	-14,309 GJ/y (SS$_{undig}$)
CO_2 reduction		
1.1 – 1.2	1,008 tonCO_2/y (PS$_{dig}$ + SS$_{dig}$)	157 tonCO_2/y (PS$_{dig}$ + SS$_{dig}$)
2.1 – 2.2	-856 tonCO_2/y (SS$_{undig}$)	-1,753 tonCO_2/y (SS$_{undig}$)

PEF for electricity. The relation between the primary energy savings performances and the PEF can be observed in Figure 3.11. It can be extrapolated that for a PEF of around 2 GJ/GJ, scenario 1.2 (only PS digested) becomes better than scenario 1.1 (PS and SS digested). The steepness of the curve (for both the couples of scenarios) indicates the measure to which the results are sensitive to this factor. Also from the graph, it can be deduced that for a PEF of around 1 GJ/GJ (all electricity provided by wind turbines) the scenarios that less (or not at all) rely on AD will perform much better than their counterparts.

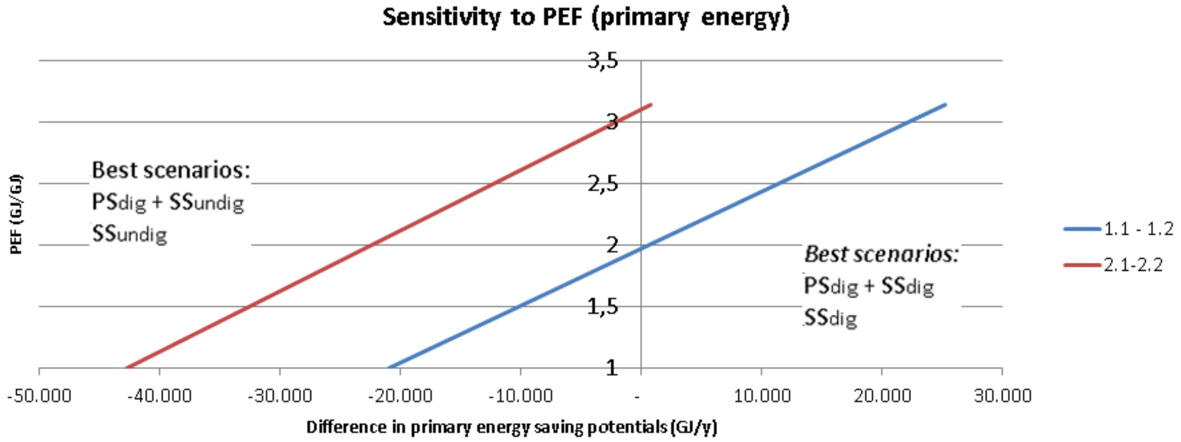


Figure 3.11: Sensitivity of primary energy savings performances to PEF.

CO_2 footprint of electricity production. As expected, scenarios 1.2 and 2.2 gained more advantage in terms of CO_2 savings potentials. Scenario 1.2 allowed for a saving of 440 tonCO_2/y more than scenario 1.1 (as opposed to the previous 1,008 tonCO_2/y advantage of scenario 1.1) and Scenario 2.2 increased its advantage to 2.219 tonCO_2/y (previous: 856 tonCO_2/y).

Figures 3.12 and 3.13 show the sensitivity of primary energy performances and CO_2 performances respectively to the different factors. The PE use factor was left out because of the uncertainty related to it. The values displayed in the graphs are the differences between the performance for the two extremes of the factor's range. In general, the drying heat type is the factor that most influences the scenarios' performances in terms of primary energy. After that, specific biogas production and biogas composition are the most influencing factors. However, as mentioned, for them to actually change, energy or chemical intensive techniques need to be used.
For CO_2 reduction performances, methane slip is the most influential factor, especially for scenario 1.1 (which is the one in which biogas production is higher).

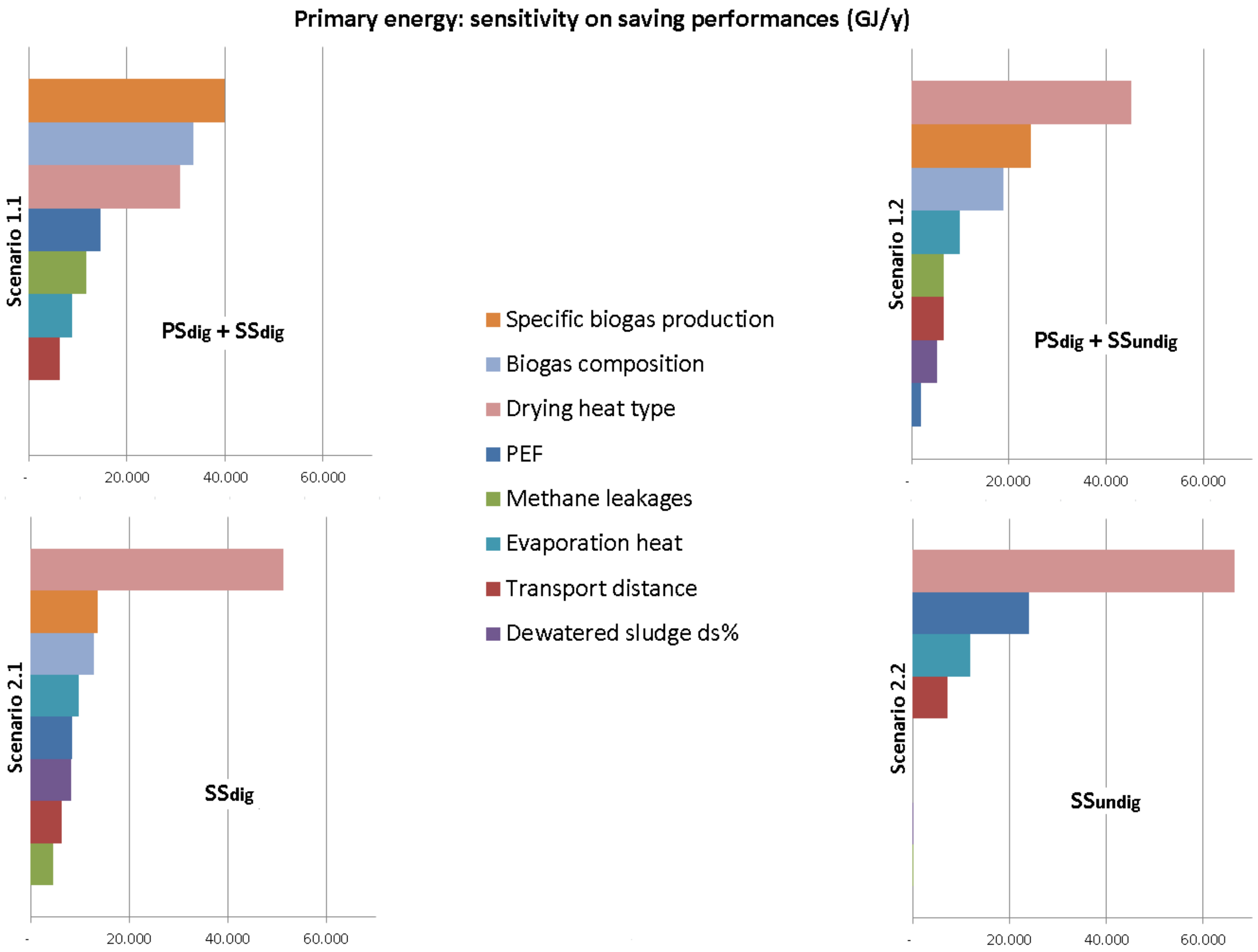


Figure 3.12: Sensitivity of primary energy saving performances.

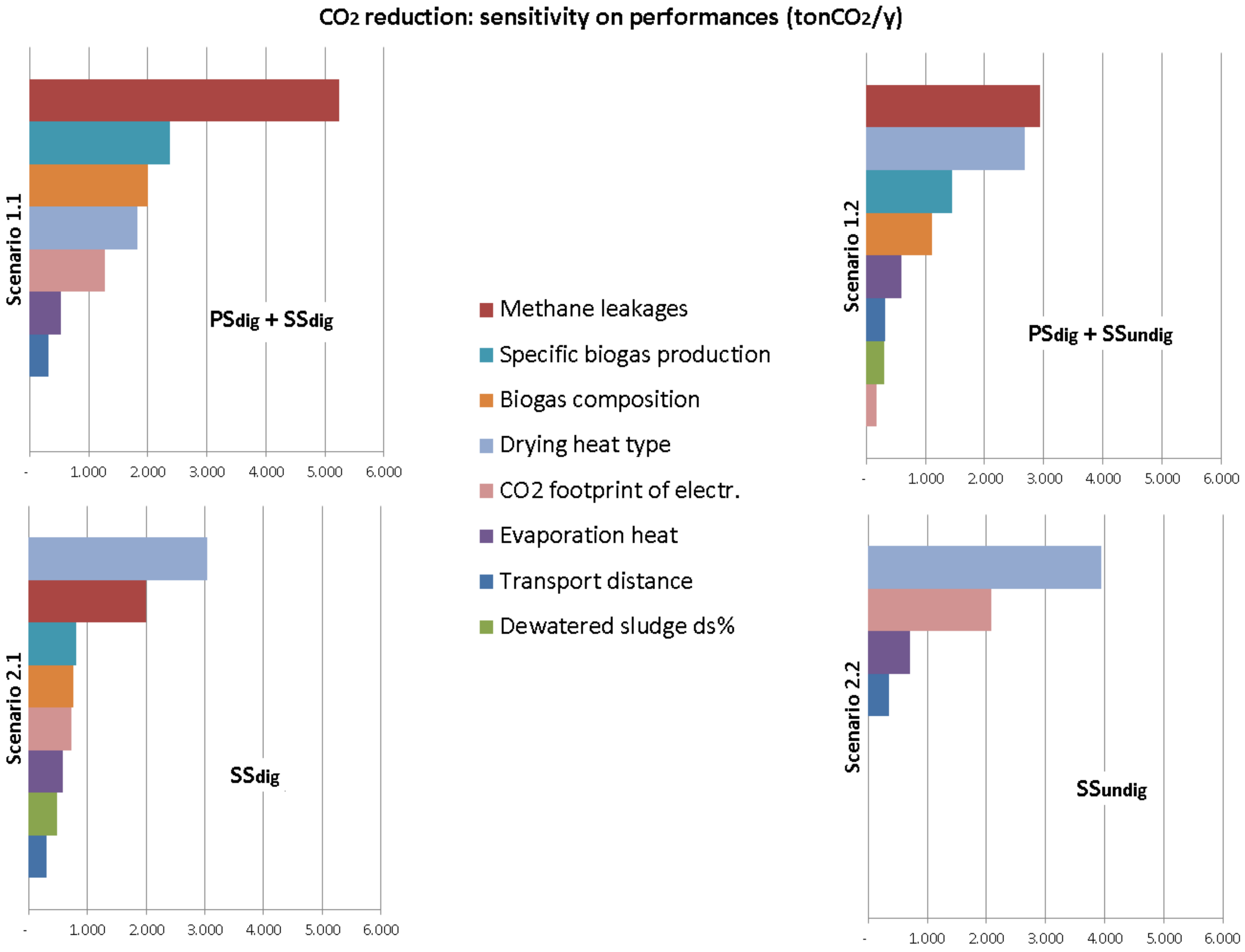


Figure 3.13: Sensitivity of CO2 reduction performances.

2020 situation with waste heat use. Given the high sensitivity of the results to PEF, CO_2 emission factor for electricity, new results were produced by tuning them at the same time and assuming the use of waste heat. Although specific biogas production and biogas composition are very influential too, they were not considered because they will not change to the higher values without conditioning techniques (which are energy and/or chemicals intensive). Basically, a likely future scenario was envisioned with the use of waste heat, and in a situation where the real values for PEF and electricity CO_2 footprint are used for 2020. For the PEF value, an average of the values for 2020 from Table 2.8 was used (1.89 GJ_{prim}/GJ_{sec}) and adapted by multiplying it by the ratio between the GER value for electricity and the commonly used PEF (11.3/2.5). The results are shown in Table 3.7.

Table 3.7. Results for 2020 situation with waste heat use.

	Base situation	2020 situation with waste heat
Primary energy savings		
1.1 – 1.2	25,219 GJ/y (PS_{dig} + SS_{dig})	2,198 GJ/y (PS_{dig} + SS_{dig})
2.1 – 2.2	791 GJ/y (SS_{dig})	-26,245 GJ/y (SS_{undig})
CO_2 reduction		
1.1 – 1.2	1,008 tonCO_2/y (PS_{dig} + SS_{dig})	-985 tonCO_2/y (PS_{dig} + SS_{undig})
2.1 – 2.2	-856 tonCO_2/y (SS_{undig})	-2,794 tonCO_2/y (SS_{undig})

The difference in primary energy performances within Maxi scenario 1 (PS+SS) shrank considerably, making the two scenarios almost equivalent. In terms of CO_2, scenario 1.2 (PS + undigested SS) became better, by 8% the average of the performances. Within Maxi scenario 2, scenario 2.2 performs better (by measure) both in terms of primary energy savings and also in CO_2 reduction performance.

3.2.3. Discussion

From the base case calculations, it can be deduced that when both primary and secondary sludge are present (Maxi scenario 1), it is better to digest both (instead of digesting primary sludge only), both in terms of primary energy saving and also CO_2 reduction. For CO_2, this is true only for methane leakages under ~4.5% of the total production. Therefore, if the biogas infrastructure is not built state-of-the-art, it is better to digest primary sludge only. For primary energy, scenario 1.1 is better for any methane leakage percentage.

When only secondary sludge needs to be treated, the two options (the implementation of AD and the direct drying of the sludge) are very similar in primary energy saving performances. However, relative to CO_2, it is better to not digest the sludge. For methane leakages higher than 2% of the total production, scenario 2.2 is better in terms of primary energy.

This means that if Waternet was to build a sludge treatment plant now, and the focus is on CO_2 reduction, should opt for AD applied to all the sludge, if the sludge is mixed, and for no AD, if the sludge is secondary only.

The sensitivity analysis for methane leakages provides additional confirmation of the fact that methane leakages in a treatment plant play a crucial role. It indeed confirms the theory expressed by Daelman et al. (2012) according to which methane leakages can cross out the benefits of valorising the biogas.

Although changing the concentrations of dry solids for the singularly digested sludges did not change the hierarchy of sustainability, it did show a significant impact on primary energy and CO_2 performances. This underlines the importance of conducting plant scale tests on sludges digested separately, to have a bigger insight on the sustainability performances of treatment trains digesting only one type of sludge. This will reveal both the achievable dry solids concentration, and also the polyelectrolytes requirement, which is another factor that is unknown and to which the results showed sensitivity.

The specific evaporation heat factor did not influence the results in a significant manner; this means that the choice of the dryer is not particularly important.

The sensitivity was performed also on biogas production potential and methane content in biogas, and these factors did change the situation when increased. However, as mentioned, in order for them to increase, special conditioning techniques need to be applied, which require energy and/or chemicals; this would change the energy and CO_2 balance altogether. These calculations are beyond the scope of this research.

A higher SS:PS ratio, implying an input of secondary sludge from other WWTPs, was another factor that did not change the hierarchy of the scenarios in terms of sustainability, meaning that the same is valid for a facility like the one of Amsterdam West. The transport distance of the dried sludge to the final user is another parameter that has no influence on the results. This is not surprising considering the small portion of the total energy input that transport has on the total energy balance.

A peculiarity of Waternet's situation is that the heat that would be used for drying is not exactly waste heat, since its retrieval entails an electricity production loss. Based on the sensitivity analysis, using actual waste heat (as it would happen in an ideal situation) makes scenario 2.2 (only secondary sludge, undigested) decisively better than 2.1, both for primary energy savings, and also for CO_2 reduction. Although scenario 1.1 (digestion of both primary and secondary sludge) still performs better than 1.2 (digestion of primary sludge only), the differences in primary energy saving and CO_2 reduction performances shrank considerably.

Another factor that showed a great impact on the primary energy savings is the PEF used. In the base case situation, scenarios 1.1 and 2.1 are better in terms of primary energy. However, when the sludge treatment is looked at as a machine, scenarios 1.2 and 2.2 prove to be more efficient, meaning that they make the most out of the energetic inputs received. The discrepancy can be explained by the PEF used, namely by the sources from which, in average, electricity is retrieved. In fact, when the factor goes close to 1 (Figure 3.10), the scenarios that are more efficient also turn the most convenient in terms of primary energy. This means that in the future, with an ever-increasing share of renewable sources in the energy mix, the scenarios less reliant on AD will be the most sustainable and the best for energy saving purposes. This can be explained by the fact that the electricity produced from the biogas and the external electricity needed in scenario 2.2 will have a less weighty role. However, it is important to stress that since the sensitivity to this factor is very high, it is vital to assess the right PEF to use. Although it is true that the PEF will decrease in time, it is not exactly clear which PEF is correct now. A thorough assessment of this value would therefore help assess the true primary energy saving potentials.

Predictably, assuming a lower CO_2 for electricity use improves the performances of scenarios 1.2 and 2.2, because the energy savings thanks to biogas and the external energy use needed by scenario 2.2 become less important.

The most interesting result emerging from the sensitivity analysis is arguably the one of the 2020 situation with waste heat. In fact, contrary to the base case calculation, in the 2020 situation, more realistic values were used for PEF and the CO_2 footprint of electricity, and the ideal situation with the use of waste heat for drying was envisioned.

This future scenario shows that if the focus is on CO_2 reduction, when mixed sludge is present it is better to only digest primary sludge; if only secondary sludge is present, not digesting it becomes even more sustainable. In terms of primary energy, when secondary sludge only is present it is decisively better to not digest it; when the sludge is mixed, it is still better to digest both primary and secondary sludge but the difference in performances is very small.

Looking at the results from an overarching perspective, the general direction seems to be that of dismissing anaerobic digestion in the future; whereas right now, it may still be more sustainable to implement it, at least in the case of mixed sludge. However, even if a sludge treatment plant was to be built now, the designer should not make a decision based on the present situation. It should be taken into account that the lifetime of the infrastructures of which such treatment plant is composed of is at least fifteen – twenty years. Therefore, a projection of sustainability should be made. Either way, when, after thorough assessment, the performances of two treatment trains are similar in terms of sustainability, what will tip the balance is the cost analysis. It can reasonably be expected that the scenarios that require less or smaller facilities (i.e. 1.2 and 2.2) will be cheaper, and an potential sustainability disadvantage could be compensated with the installation of solar panels.

3.3. Final remarks

It is useful to have these two parts of research separate. For example, as it happened in the case of Weesp's new WWTP, if the sludge is to be sent to another facility, then the focus is on the waterline only. Similarly, if a sludge treatment train is being analysed, receiving different types and amounts of sludge (like it happens in Amsterdam West) with no control over it, then it makes sense to perform a research like the one answering the second research question in this study. However, if a new treatment plant with an onsite final sludge disposal is to be designed, then it is useful to perform an extensive assessment of primary energy consumption, CO_2 footprint and costs.

For instance, if a 500,000 PE WWTP was to be built in 2020, a system selection study should be performed analysing 4 main scenarios:

- Waterline with primary sedimentation and 1.1 option for sludge treatment;
- Waterline with primary sedimentation and 1.2 option for sludge treatment;
- Waterline without primary sedimentation and 2.1 for sludge treatment;
- Waterline without primary sedimentation and 2.2 for sludge treatment.

In fact, if we compare the amounts of primary energy and CO_2 saved between the sludge options for mixed sludge and for secondary sludge only, the former are much higher (see Table 3.3) and higher than the CO_2 difference in CO_2 footprint between configuration 1 and 2 (see Table 3.1). Therefore, this could influence the choice upstream (whether to implement primary sedimentation or not). The choice cannot be predicted by just the results from this study because the sludge treatment considered for the first part of the research (incineration of dewatered sludge) was different from the one used in the second part (creation of a biofuel by drying the sludge).

Again, in any case the final choice needs to take costs into consideration, because the most sustainable option might be too expensive to compete with other sustainability measures (i.e. solar panels).

The future trend that can be deduced (and that is true both for the waterline related choices and strictly sludge line related choices) is that with an increased share of renewable energies in the mix, the electricity produced from the valorisation of the biogas will have an ever lower sustainability potential. In terms of cost, the prices of energy off the grid are destined to decrease, as are the costs of solar panels; that said, regardless of which option is more sustainable, solar panels and other renewable techniques will become more and more appealing with time.

4. Conclusions and recommendations

The goal of becoming carbon neutral by 2020 is not an easy one. However, by making sludge treatment more sustainable, wastewater managers and water boards can help reach that goal faster. It is not just about what choices are most sustainable; it is also about the cost of the different choices of sustainability. The way to make sludge related treatments more sustainable for Waternet is not a straightforward answer; rather, it requires tailor made calculations. However, as it emerged from the present study, applying primary sedimentation in a plant with Weesp's characteristics is not financially convenient even for scales bigger than 500,000 PE. In fact, alternative sustainability measures like solar panels are much cheaper.

It also emerged that when primary sedimentation is not implemented, it is more sustainable (in terms of CO_2 reduction) to not digest the secondary sludge and to directly dry it; when the sludge instead is mixed, it is better to digest all of it rather than just primary. However, in the latter case the differences are narrow, only relative to the present time and for the use of a certain drying heat. An analysis projected to 2020 with the use of waste heat showed that the less or not at all reliant on anaerobic digestion treatment trains will be more sustainable. A future research should determine whether the most sustainable scenarios are also financially convenient, i.e. whether it might be cheaper to use the less sustainable scenario and make up for the carbon dioxide offset with alternative measures (such as solar panels). In order to perform a thorough analysis, the sustainability performance should be calculated based on substitution values (such as GER values) that take into account the whole production chain. Moreover, more research should be conducted about singularly digested and undigested types of sludge and their behaviour.

Thus, the main recommendation that stems from this study is that for future plants, since the production of biogas will be less and less important, the option of not implementing primary sedimentation and anaerobic digestion for secondary sludge should be considered. In addition to this, a financial analysis should always be conducted and the price of sustainability should be calculated and compared with other alternatives (solar panels, wind turbines, etc.).

Reference list

Alyaseri, I., & Zhou, J. (2017). Towards better environmental performance of wastewater sludge treatment using endpoint approach in LCA methodology. *Heliyon*, *3*(3), e00268.

Andreoli, C. V., Von Sperling, M., Fernandes, F., & Ronteltap, M. (2007). *Sludge treatment and disposal*. Biological Wastewater Treatment Series, Volume Six, IWA publishing.

Babatunde, A. O., & Zhao, Y. Q. (2007). Constructive approaches toward water treatment works sludge management: an international review of beneficial reuses. *Critical Reviews in Environmental Science and Technology*, *37*(2), 129-164.

Barnaby, W. (2009). Do nations go to war over water? *NATURE*, *458*, 19.

Berg, R., Reitsma, B., de Vries, A., Geerse, H., van der Velde, I., (2015). *Watertakenplan Fluvius 2016-2021*, Specificatie Waterschap Reest en Wieden, Module A - Integraal Zuiveringsplan, Available at: http://www.samenwerkenmetwater.nl/fileadmin/downloads/SWMW_2/8836_ab_jw_bijlage_2_fluvius_specif_wrw_izp_vs_20151102_klein_formaat.pdf

Casey, T. J. (2006). Unit treatment processes in water and wastewater engineering. West Sussex, England: Wiley.

Clavreul, J., Baumeister, H., Christensen, T. H., & Damgaard, A. (2014). An environmental assessment system for environmental technologies. Environmental Modelling & Software, 60, 18-30. DOI: 10.1016/j.envsoft.2014.06.007

CO2 emissiefactoren, n.d. Available at www.co2emissiefactoren.nl [Accessed 14 June 2017]

Daelman, M. R., van Voorthuizen, E. M., van Dongen, U. G., Volcke, E. I., & van Loosdrecht, M. C. (2012). Methane emission during municipal wastewater treatment. Water research, 46(11), 3657-3670.

van Doorn, J., van de Kamp, W. L., (2009). Verwerking van zeefgoed voor duurzame energieopwekking, ECN-X-09-141.

Esser, A., Sensfuss, F., (2016). Evaluation of primary energy factor calculation options for electricity, *Fraunhofer-Institut für System- und Innovationsforschung (ISI)*, ENER/C3/2013-484.

Frijns, J., Mulder, M., & Roorda, J. (2009). Climate footprint and mitigation measures in the Dutch water sector. *Climate Change and Water, International Perspectives on Mitigation and Adaptation*, 73-80.

Frijns, J., Hofman, J., & Nederlof, M. (2013). The potential of (waste) water as energy carrier. *Energy Conversion and Management*, *65*, 357-363.

Fritsche, U. R., & Greß, H. W. (2015). Development of the Primary Energy Factor of Electricity Generation in the EU-28 from 2010-2013. *International institute for sustainability Analysis and Strategy, Darmstadt*.

Gavala, H. N., Yenal, U., Skiadas, I. V., Westermann, P., & Ahring, B. K. (2003). Mesophilic and thermophilic anaerobic digestion of primary and secondary sludge. Effect of pre-treatment at elevated temperature. *Water research*, *37*(19), 4561-4572.

Gerdes, J. (2013). CO_2-emissies en primair fossiel energiegebruik van elektriciteit in Nederland–aanvulling 2020, 2025 en 2030. *Policy Studies*, *ECN-N--13-017.*

Gori, R., Jiang, L. M., Sobhani, R., & Rosso, D. (2011). Effects of soluble and particulate substrate on the carbon and energy footprint of wastewater treatment processes. *water research*, *45*(18), 5858-5872.

Gori, R., Giaccherini, F., Jiang, L. M., Sobhani, R., & Rosso, D. (2013). Role of primary sedimentation on plant-wide energy recovery and carbon footprint. *Water Science and Technology*, *68*(4), 870-878.

Gourdet, C., Girault, R., Berthault, S., Richard, M., Tosoni, J., & Pradel, M. (2017). In quest of environmental hotspots of sewage sludge treatment combining anaerobic digestion and mechanical dewatering: A life cycle assessment approach. *Journal of Cleaner Production*, *143*, 1123-1136.

De Graaff, M., Zandvoort, M., Janse, T., Frijns, J., Roest, K. (2011). Methaan- en lachgasemissies in de Amsterdamse waterketen: omvang en reductiemogelijkheden.

Hauck, M., Maalcke-Luesken, F. A., Jetten, M. S., & Huijbregts, M. A. (2016). Removing nitrogen from wastewater with side stream anammox: What are the trade-offs between environmental impacts?. *Resources, Conservation and Recycling*, *107*, 212-219.

Hjort-Gregersen, K., (2014). Methane Emission From Danish Biogas Plants; Economic Impact of Identified Methane Leakages Project: ForskEl 2013-1-12093. AGROTECH (www.agrotech.dk), Denmark.

Hong, J., Hong, J., Otaki, M., & Jolliet, O. (2009). Environmental and economic life cycle assessment for sewage sludge treatment processes in Japan. *Waste Management*, *29*(2), 696-703.

Hospido, A., Moreira, T., Martín, M., Rigola, M., & Feijoo, G. (2005). Environmental evaluation of different treatment processes for sludge from urban wastewater treatments: Anaerobic digestion versus thermal processes (10 pp). *The International Journal of Life Cycle Assessment*, *10*(5), 336-345.

Houillon, G., & Jolliet, O. (2005). Life cycle assessment of processes for the treatment of wastewater urban sludge: energy and global warming analysis. *Journal of cleaner production*, *13*(3), 287-299.

HUBER SE. (2017). Retrieved June 21, 2017, from http://www.huber.de/solutions/sludge-treatment/sludge-drying/middle-temperature-drying.html

IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. & Miller, H.L. (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA.

Klaversma, E., van der Helm, A. W. C., & Kappelhof, J. W. N. M. The use of life cycle assessment for the reduction of indirect greenhouse gas emissions in the Amsterdam water cycle.

Komline-Sanderson. (n.d.). Accessed June 21, 2017, from http://www.komline.com/docs/sludge_dryer.html

Lensink, S.M., Cleijne, J.W., (2016): Eindadvies basisbedragen SDE+ 2017, retrieved from www.ecn.nl

Van Loosdrecht, M. C., Kuba, T., van Veldhuizen, H. M., Brandse, F. A., & Heijnen, J. J. (1997). Environmental impacts of nutrient removal processes: case study. *Journal of environmental engineering*, *123*(1), 33-40.

Lu, J., & Ahring, B. K. (2007). Optimization of Anaerobic Digestion of Sewage Sludge Using Thermophilic Anaerobic Pre-Treatment.

Metcalf & Eddy, Burton, F. L., Stensel, H. D., & Tchobanoglous, G. (2003). *Wastewater engineering: treatment and reuse*. McGraw Hill.

Min, S. K., Zhang, X., Zwiers, F. W., & Hegerl, G. C. (2011). Human contribution to more-intense precipitation extremes. *Nature*, *470*(7334), 378-381.

Mininni, G., Blanch, A. R., Lucena, F., & Berselli, S. (2015). EU policy on sewage sludge utilization and perspectives on new approaches of sludge management. *Environmental Science and Pollution Research*, *22*(10), 7361-7374.

Murray, A., Horvath, A., & Nelson, K. L. (2008). Hybrid life-cycle environmental and cost inventory of sewage sludge treatment and end-use scenarios: a case study from China.

Naroznova, I., Møller, J., & Scheutz, C. (2016). Global warming potential of material fractions occurring in source-separated organic household waste treated by anaerobic digestion or incineration under different framework conditions. *Waste management*, *58*, 397-407.

Nugent, D., & Sovacool, B. K. (2014): Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey. *Energy Policy*, *65*, 229-244.

Oshita, K., Okumura, T., Takaoka, M., Fujimori, T., Appels, L., & Dewil, R. (2014). Methane and nitrous oxide emissions following anaerobic digestion of sludge in Japanese sewage treatment facilities. *Bioresource technology*, *171*, 175-181.

Provincie Noord-Holland, 2016: *Aanvragen windparken*. Available at: https://www.noord-holland.nl/Onderwerpen/Duurzaamheid_Milieu/Projecten/Wind_op_land/Aanvragen_windparken [Accessed 8 May 2017].

RVO, 2017: GER-waarden Database. Available at http://www.rvo.nl/file/ger-waarden-en-co2-lijst-januari-2017

Senter Novem (2007). Cijfers en tabellen 2007, Available at http://www.freitas.nl/download.htm

STOWA (2010). Slibketenstudie II, nr. 2010-33.

STOWA (2011)[a]. Handboek slibgisting, nr. 2011-16.

STOWA (2011)[b]. Optimalisatie WKK en biogasbenutting, nr. 2011-33.

STOWA (2012). GER-waarden en milieu-impactscores productie van hulpstoffen in de waterketen, nr. 2012-06.

TU Delft, (n.d.): Wastewater treatment, Delft University of Technology, Year accessed: 2017.

Unie van Waterschappen. (n.d.). Retrieved June 14, 2017, from https://www.uvw.nl/

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., (2016). The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, [online] 21(9), pp.1218–1230. Available at: <http://link.springer.com/10.1007/s11367-016-1087-8> [Accessed 12 May 2017].

Yoshida, H., Mønster, J., & Scheutz, C. (2014). Plant-integrated measurement of greenhouse gas emissions from a municipal wastewater treatment plant. Water research, 61, 108-1

Appendix 1

A1.1. Plant scale: 500,000 PE

Table A1.1: Influent characteristics.

Description	Unit of measure	Basis	Scale up
Load (à 150 g TZV)	PE	46,000	500,000
Average flowrate	m^3/d	11,860	128,913
DWF flowrate	m^3/d	9,128	99,217
DWF period	h	14	14
DWF flow rate	m^3/h	652	7,087
RWF flowrate	m^3/h	1,800	19,565
COD load	kg/d	4,889	53,141
BOD load	kg/d	1,925	20,924
SS load	kg/d	2,674	29,065
N-kjeldahl load	kg/d	440	4,783
P-total load	kg/d	63	685
BOD/N	-	4,4	4
BOD/P	-	31	31

Table A1.2: Dimensioning of the influent pumps.

Description	Unit of measure	46,000 PE	500,000 PE
Average flow	m^3/h	652	7,087
Maximum flow	m^3/h	1,800	19,565
Number of pumps	st	4	4
RWF pump 1 (+fo)	m^3/h	900	9,800

RWF pump 2 (+fo)	m^3/h	900	9,800
DWF pump 3 (+fo)	m^3/h	450	4,900
DWF pump 4 (+fo)	m^3/h	450	4,900

Table A1.3: Dimensioning of the bar screens.

Description	Unit of measure	46,000 PE	500,000 PE
Number of units	pieces	2	2
Capacity per unit	m^3/h	950	9,800
Design capacity	m^3/h	950	19,600
Slit width or pore size	mm	6	6
Dewatering presses	pieces	2	2

Table A1.4: Dimensioning of the sand traps.

Description	Unit of measure	46,000 PE	500,000 PE
Type of sand trap	-	Jeta zandvanger	
Capacity	m^3/uur	1,900	9,800
Number of units	pieces	1	2
Equipped with sand washer	-	yes	yes
Sand storage tanks	pieces	1	1

Table A1.5: Dimensioning of the primary sedimentation tank.

Description	Unit of measure	46,000 PE	500,000 PE
Number of units	st	1	3
Surface load (RWF)	m^3/m^2/h	4	4
HRT (RWF)	H	0.5	0.5
Surface load (DWF)	m^3/m^2/h	1.4	1.4
HRT (DWF)	h	1.5	1.5
Surface	m^2	475	1,721
Diameter	m	24.6	46.8
Side depth	m	3	3

Table A1.6: Dimensioning of the primary sludge line.

Description	Unit of measure	46,000 PE	500,000 PE
Avg amount of pr. sludge	kg ds/d	1,337	14,533
Variation amount of primary sludge	-	2	2
Design quantity	kg ds/d	2.674	29,065
Conc. of extracted pr. sludge	kg/m³	6	6
Number of pumps and extenders	st	2 (1 is reserve)	6 (3 are reserve)
Capacity per pump	m^3/h	19	67.3
Thickener			
Surface load	$kg\ ds/m^2.d$	40	40
Number of tanks	st	1	2
Surface	m²	33.4	363.3
Effective height	m	3	3
IPS pumps			
Concentration thickened sludge	kg ds/m³	45	45
Drain time thickened pr. Sludge	h/d	16	16
Number of pumps	st	2 (1 is reserve)	4 (2 are res.)
Capacity (design)	m^3/uur	2	10.25
PS buffer			
Number of units	st	1	1
Buffer time	d	4	4
Avg quantity of primary sludge	m³/d	30	326
Effective V of sludge buffer	m³	119	1,304
Effective height	m	3	3
Total height	m	4.5	4.5
Total gross volume	m³	180	1,957

Table A1.7: Dimensioning of the activated sludge process.

Description	Unit of measure	46,000 PE		500,000 PE	
Activated sludge tank		No pretr.	With pretr.	No pretr.	With pretr.
Design biomass concentration	kg ds/m³	4.6	4.6	4.6	4.6

Response time	%	100	100	100	100
Sludge load	kg BOD/kg ds.d	0.067	0.075	0.067	0.075
BOD/N ratio incoming to AT	-	4.4	3.3	4.4	3.3
Volume anaerobic tank	m^3	1,304	1,304	14,174	14,174
Volume anoxic tank	m^3	836	1,024	9,087	11,130
Volume aerobic tank	m^3	6,480	3,314	70,435	36,022
Design excess sludge production*	kg ds/d	2,426	1,424	26,370	15,478
		8,620	5,642	93,696	61,326
Aeration					
Oxygenation	kg O_2/h	439	364	4,772	3,957
Total aeration capacity	Nm^3/h	2 x 1,705=3,410	2x 1,415=2,830		
Secondary sedimentation tank					
Number of units	st	1	1	10	10
Surface	m^2	2,115	2,115	22,989	22,989
Diameter	m	51.9	51.9		

Table A1.8: Dimensioning of the secondary sludge line.

Description	Unit of measure	46,000 PE		500,000 PE	
Excess sludge pumps		No pretr.	With pretr.	No pre tr.	With pre tr.
Maximum sludge production	kg ds/d	2,426	1,424	26,370	15,478
Conc. Of surplus sludge	kg ds/m^3	6	6	6	6
Additional reduct. sludge conc. (in AT)	kg ds/m^3	0.1	0.1	0.1	0.1
Additional extracted sludge load	kg ds/d	713	499	7,750	5,424
Flow rate of extracted excess sludge (constant situation)	m^3/d	404	237	4,391	2,576
Additional (peak) Flow rate of extracted surplus sludge	m^3/d	119	83	1,293	902
Total capacity of sludge pumps	m^3/d	523	321	5,685	3,489
Drain time of secondary sludge	h/d	16	16	16	16
Number of pumps	St	2 (1 is reserve)	2 (1 is reserve)	20 (10 res.)	(20 (10 res.)
Capacity per pump	m^3/h	32.7	20	36	22

Belt thickener					
Maximum capacity per pump	m^3/h	32.7	20	36	22
PE-dosing 0,1% (see: chem. dosering)	m^3/h	0.7	0.4	7.6	4.3
Total flow rate	m^3/h	33.4	20.4	363.0	221.7
Number of belt thickeners	St	2 (1 is reserve)	2 (1 is reserve)	3 (1 is reserve)	3 (1 is reserve)
Max return sludge concentration	kg ds/m^3	10	10	10	10
Max dry solids load	kg ds/h	330	200	3,587	2,174
Thickened excess sludge pump					
Number of pumps	stuks	1	1	3 (1 reserve)	3 (1 reserve)
Sludge load extracted	kg ds/h	330	200	3,587	2,174
Dry solids content	kg ds/m^3	60	60	60	60
Pump capacity (design)	m^3/h	5,5	3,3	30	18
Excess sludge buffer					
Number of buffers	stuks	1	1	2	1
Average flow	m^3/d	50	31	543	337
Number of buffer days	d	4	4	4	4
Effective volume	m^3	200	122	2,174	1,326
Effective height	m	3	3	3	3
Surface	m^2	67	41	362	442
Total height	m	4.5	4.5	4.5	4.5
Total gross volume	m^3	300	184	1,630	1,989

Table A1.9: Energy balance.

ENERGY – IN (kWh/y)	46,000		500,000	
Scenario	No pretr.	With pretr.	No pretr.	With pretr.
Influent pumps	174,759	174,759	1,899,558	1,899,558
Coarse screen + sandtrap	18,555	18,555	201,685	201,685
Pre-sedimentation (tank + pumps)	-	50,718	-	551,279

Activated sludge tank (recirculation, pump)	160,226	120,486	1,741,583	1,309,632
Aeration	441,862	371,720	4,802,852	4,040,438
Secondary clarifier (return sludge)	152,160	152,160	1,653,913	1,653,913
Sliblijn	37,156	41,350	403,873	449,453
Air treatment	35,730	35,730	388,370	388,370
Various (chemicals + other)	163,987	163,987	1,782,463	1,782,463
Energy needed for dewatering (WEST)	51,487	53,545	559,640	582,013
Totaal	**1,235,922**	**1,183,010**	**13,433,936**	**12,858,802**
ENERGY – OUT (kWh/y)				
Energy out of biogas	366,415	746,078	3,982,773	8,109,542
Energy out of incineration	163,812	162,311	1,780,563	1,764,255

Table A1.10: CO_2 balance.

			46,000		500,000	
Contributor	**Factor**	**Unit of measure**	**No pretr.**	**With pretr.**	**No pretr.**	**With pretr.**
Reinforced concrete	0.,057	kg CO2/kg concrete	11,746	11,853	97,668	97,333
PE consumption	2.13	kg CO_2/kg PE actief	22,964	21,992	249,608	239,044
Aluminium consumption	0.537	kg CO_2/kg $AlCl_3$	0	14,976	0	162,782
Sludge transport	0.115	kg CO2/ton.km	54,276	73,914	589,954	803,418
Energy in total	0.67	kg CO_2/kWh	829,798	794,273	9,019,545	8,633,400
Energie out total	-0.67	kg CO_2/kWh	-355,994	-609,893	-3,869,504	-6,629,267

Energy (net)	0.6714	kg CO_2/kWh	473,804	184,380	5,150,041	2,004,133
CO_2 balance		kg CO_2/year	**562,789**	**307,116**	**6,087,271**	**3,306,710**

Table A1.11: Reinforced concrete amounts (500,000 PE).

COMPONENTS	**Concrete (m3) (no primary sed.)**	**Concrete (m3) (with prim. sed.)**
Influent pumps case + sandtrap	823	839
Primary clarifiers		2.053
Activated sludge tanks	11.022	8.547
Secondary clarifiers	8.091	8.091
Recirculation sludge pumps	135	135
Primary sludge thickener		254
Primary sludge buffer tank		284
Secondary sludge buffer	491	288
Total (m3)	20.562	20.491
Total (ton)*	51.404	51.228
Total (kg)*	51.404.308	51.227.690

(*) Specific weight of reinforced concrete: 2500 kg/m^3

Appendix 2

Table A2.1. Overview of construction costs.

	46,000 PE				500,000 PE			
Construction costs	**No presed.**		**With presed.**		**No presed.**			
	Civil	Mechanical	Civil	Mechanical	Civil	Mechanical	Civil	Mechanical
Influent pumping equipment	180,000	266,000	180,000	266,000	593,442	876,976	593,442	876,976
ONW + Sandtrap	411,000	195,000	424,000	195,000	1,866,844	885,729	1,866,844	885,729
Bar screen		230,000		230,000		758,288		758,288
Primary sedimentation tank with rotating bridge			460,000	344,000			3,786,741	1,964,378
Primary sludge pump				71,000				400,818
Splitbox between primary clarifier and A.T.							500,000	
Blower building	314,000		314,000		628,000		628,000	
Activated sludge tanks with aeration	1,456,000	237,000	1,143,000	204,000	10,243,885	2,576,087	8,618,970	2,217,391
Mixers and pumps (aeration tanks)		204,000		203,000		2,217,391		2,206,522
Secondary sedimentation tanks (incl. skimmers)	694,000	302,000	694,000	302,000	7,294,230	3,148,568	7,294,230	3,148,568
Recirculation sludge pumps	69,000	213,000	69,000	194,000	227,486	702,240	227,486	639,599
Primary sludge thickener with agitator			94,000	84,000			438,441	391,799
Primary sludge buffertank with mixer and bridge			117,000	24,000			387,355	79,457
Primary sludge thickener pumps				44,000				199,218
Belt thickener building	147,000		147,000		294,000		294,000	
Sludge pumps		116,000		107,000		1209,152		1,024,708
Belt thickener		202,000		163,000		706,372		569,994
Secondary sludge thickener pumps		70,000		59,000		244,783		207,356
SS buffer with bridge and mixer	144,000	26,000	116,000	24,000	671,403	121,226	382,441	79,126

Company building	485,000		485,000		582,000		582,000	
Pavements and pipes	743,000		813,000		4,053,085		4,467,120	
Terrain and drainage	123,000		123,000		1,202,008		1,242,679	
Air treatment		165,000		226,000		543,989		745,100
Chemical dosing	50,000	59,000	50,000	59,000	164,845	641,304	164,845	641,304
PE dosing (belt thickener)		52,000		52,000		171,439		171,439
Business and drinking water plant		67,000		67,000		220,892		220,892
Compressed air system		22,000		22,000		72,532		72,532
Ground pumping station		45,000		45,000		148,361		148,361
Heating and ventilation		45,000		45,000		148,361		148,361
Electrotechnical 40 %		1,006,000		1,212,000		6,157,476		7,119,166
PA 10%		252,000		303,000		1,539,369		1,779,792
Subtotal direct construction costs	4,816,000	3,774,000	5,229000	4,545,000	27,821,230	23,090,534	31,474,596	26,696,874
Subtotal direct construction costs (Civil + Mechanical)		**8,590,000**		**9,774,000**		**50,911,764**		**58,171,469**
further detailing construction costs (17%)		1,460,300		1,661,580		8,655,000		9,889150
Direct construction costs		10,050,300		11,435,580		59,566,763		68,060,619
One off costs (1%)		100,503		114,356		595,668		680,606
General site costs (5%)		502,515		571,779		2,978,338		3,403,031
Implementation (8%)		804,024		914,846		4,765,341		5,444,850
Overheads (7%)		802,014		912,559		4,169,673		4,764,243
Profit and risk (5%)		612,968		697,456		2,978,338		3,403,031
Total construction costs		**12,872,324**		**14,646,577**		**75,054,122**		**85,756,380**
Unforeseen (15%)		1,930,849		2,196,986		11,258,118		12,863,457
Temporary facilities (2%)		257,446		292,932		1,501,082		1,715,128
Building fixtures and office (2%)		257,446		292,932		1,501,082		1,715,128
Staff training (1%)		128,723		146,466		750,541		857,564

Insurance and construction period interest (4.5 %)		579,255		659,096		3,377,435		3,859,037
Communication (2%)		257,446		292,932		1.501.082		1,715,128
Extern consultancy costs (10 %)		1,287,232		1,464,658		7,505,412		8,575,638
Consultancy costs OG (10 %)		1,287,232		1,464,658		7,505,412		8,575,638
Fees/charges (3 %)		386,170		439,397		2,251,624		2,572,691
VAT (21%)		3,689,852		4,198,441		15,761,366		18,008,840
Total investment costs (incl. VAT)		**22,933,976**		**26,095,073**		**127,967,278**		**146,214,628**
		1.78165		1.78165				
Composition								
Civil		0.5607		0.5350		0.5465		0.5411
Mechanical		0.2929		0.3100		0.3024		0.3060
Electrical		0.1171		0.1240		0.1209		0.1224
Procesautomatisering		0.0293		0.0310		0.0302		0.0306
		1		1		1		1

Table A2.2. Overview of the basic assumptions.

Depreciation period for constructions	30	years	
Depreciation period for mechanical components	15	years	
Depreciation period for electrical components	15	years	
Depreciation period for Process Automation	7	years	
Factor for foundation costs	1.78	Includes:	incompleteness surcharge, insurance, taxes, permits, utilities, land survey, fees, installation costs, consultancy costs - and supervision, interest during construction, contingencies and VAT
Interest rate for capital costs	3,75%		
Annuity for building	0.056		
Annuity for mechanical/electrical components	0.088		
Annuity electrical	0.088		

Annuity Process Automation	0.165		
Maintenance civil engineering works	0.50%	of the construction costs excl VAT	
Maintenance of new mechanical and electrical works for sewage treatment plants	3%	of the construction costs excl VAT	
Unforeseen maintenance costs	10%	based on maintenance	
Energy costs	0.10	€ per kWh, incl VAT and all	
Personnel costs	100,000	€ per fte per year	
Sludge handling costs (no prim. sed.) (SS)	492	€ per ton ds dewatering + processing + sludge transport from Weesp CSI, incl VAT	
Sludge handling costs (with prim. sed.) (PS)	432	€ per ton ds dewatering + processing + sludge transport from Weesp CSI, incl VAT	
Sludge handling costs (with prim. sed.) (SS)	499	€ per ton ds dewatering + processing + sludge transport from Weesp CSI, incl VAT	
$FeCl_3$ (40% solution)	120	€ per ton excl VAT	
$FeClSO_4$ (41%)	124	€ per ton excl VAT (for orders >10 ton)	
$AlCl_3$ (30,7%)	125	€ per ton excl VAT	
Polyelectrolytes (42%)	1,850	€ per ton excl VAT	
Maintenance costs			
Civil works / constructions	0.5	% of construction costs CT / B	
Mechanical engineering	2	% of construction costs WTB	
Electrotechnical	4	% of construction costs E	
Process automation	10	% of construction costs PA	
Maintenance devices / general services	10	% van bouwkosten inrichting / alg. voorzieningen	
Depreciation period			

Wastewater / Wastewater installations			
Transport lines 40 years	40	years	
Construction and civil work	40	years	
Completed WWTP	30	years	
WTB	20	years	
E/ Technical installations	15	years	
Process automation	7	years	