Optimal Processing Pathway for Sludge-to-Energy Technologies: A Superstructure Optimization-Based MINLP Model

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The perception of sewage sludge has been increasingly changing from being a waste, that is a burden to the environment and society, to a useful resource of materials and renewable energy. There are several available technologies at different stages of maturity that aim to convert sludge to energy in the form of electricity and/or fuels. In this study, a decision-making support tool is proposed to help in choosing the optimal pathway for the sludge-to-energy conversion from a techno-economic perspective. The conversion technologies under study are anaerobic digestion, pyrolysis, gasification, incineration, supercritical water oxidation, supercritical water gasification as well as the corresponding dewatering and drying methods for each technology. Different synergies between the available technologies are compared by the formulation of a superstructure optimization problem expressed in a mixed-integer non-linear program (MINLP) model.

The applicability of the proposed model is explored via a case study for a hypothetical sludge treatment plant with a capacity of 100 tonnes of dry solids (tDS) per day. The model was solved via BARON solver using GAMS software within a reasonable CPU time of 70 seconds. The case study results show that fast pyrolysis technology, coupled with filter press dewatering and thermal drying as pretreatment steps, show the most promising results with the minimum treatment cost of $180/tDS. Fast pyrolysis converts the sludge to bio-oil that can be used as an alternative fuel after further refining and biochar which can be used for soil amendment or adsorption purposes. The model parameters are subject to uncertainty that was addressed in the sensitivity analysis section of the study. The pyrolysis pathway showed a high degree of robustness in most of the sensitivity scenarios. Anaerobic digestion coupled with fast pyrolysis was chosen as the best energy recovery alternative upon increasing electricity prices. The optimization model proposed in this study can be used as an early screening tool for decision-makers to assess different sludge-to-energy pathways. It can be further extended to account for different feedstocks (co-processing) and to account for environmental constraints (CO_2 emissions).

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Dedication

To my brother in heaven, Youssef

and my brother on earth, Yaseen.

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List of Abbreviations

CHP	Combined heat and power
DS	Dry solids
MAD	Mesophilic anaerobic digestion
MCDM	Multi-criteria decision-making
MHF	Multiple hearth furnaces
MILP	Mixed-integer linear programming
MINLP	Mixed-integer non-linear program
MM	Million
MSW	Municipal solid waste
SCW	Supercritical water
SCWG	Supercritical water gasification
SCWO	Supercritical water oxidation
SRT	Solids retention time
tDS	tonnes of dry solids
THP	Thermal hydrolysis pretreatment
tVS	tonnes of volatile solids
USD	United States Dollar
VS	Volatile solids
VSD	Volatile solids destruction
WAS	Waste activated sludge
WWTPs	Wastewater treatment plants

Nomenclature

A. Subscripts and Superscripts

Generic

i,j,k	Aliases of subscripts identifiers for feed, process, and product blocks.
s	Generic identifier of a process stream
c	Generic identifier of a component in a stream

Feed Source

TH	Thickened Sludge

Technologies / Processes

MAD	Mesophilic Anaerobic Digestion
MADT	MAD + Thermal Hydrolysis Pretreatment
CD	Centrifuge dewatering for digested sludge
CU	Centrifuge dewatering for undigested sludge
BPD	Belt press dewatering for digested sludge
BPU	Belt press dewatering for undigested sludge
FPD	Filter press dewatering for digested sludge
FPU	Filter press dewatering for undigested sludge
TD	Thermal Drying
INC	Incineration
GN	Gasification
PY	Fast Pyrolysis
SCO	Supercritical Water Oxidation
SCG	Supercritical Water Gasification

Final Products

DS20	20% dewatered digested sludge
DS40	40% dewatered digested sludge
ASH	Ash
E	Electricity
FERT	Class-A Biosolids (Fertilizer)
BO	Bio-oil from pyrolysis
BC	Biochar from pyrolysis
H2	Hydrogen

Process Streams

THS	Thickened Sludge
ADS	Anaerobically Digested Sludge
E	Electricity
P	Polymer for chemical conditioning
L	Lime for chemical conditioning
FC	Ferric chloride for chemical conditioning
DWS	Dewatered Sludge
TDS	Thermally dried sludge
ASH	Ash
BO	Bio-oil
BC	Biochar
H2	Hydrogen

Components in Process Streams

VS	Total volatile solids
ASH	Ash
DS	Total dry solids (VS + Ash)
W	Water or moisture in the sludge/biosolids
E	Electricity
BO	Bio-oil
BC	Biochar
H2	Hydrogen

B. Sets

I	Combined set of Feed, process, and final product blocks
FEED	Subset of feed blocks, $\mathbf{FEED} \subset \mathbf{I}$
PROCESS	Subset of processing technologies, $\mathbf{PROCESS} \subset \mathbf{I}$
PRODUCT	Subset of final products, $\mathbf{PRODUCT} \subset \mathbf{I}$
STR	Set of process streams
CHEM	Subset of chemicals streams used for conditioning $\mathbf{CHEM} \subset \mathbf{STR}$
COMP	Set of components of process streams
$\mathbf{S}_i$	Set of descendant block(s) from block $i \in \mathbf{FEED} \cup \mathbf{PROCESS}$. Where $\mathbf{S}_i \subset \mathbf{PROCESS} \cup \mathbf{PRODUCT}$
$\mathbf{P}_i$	Set of precedent block(s) of block $i \in \mathbf{PROCESS} \cup \mathbf{PRODUCT}$. Where $\mathbf{P}_i \subset \mathbf{FEED} \cup \mathbf{PROCESS}$
$\mathbf{STF}_i$	Set of inlet stream(s) applicable with process $i \in \mathbf{PROCESS}$. Where $\mathbf{STF}_i \subset \mathbf{STR}$

$\mathbf{STPR}_i$ Set of outlet stream(s) applicable with process $i \in \mathbf{PROCESS}$. Where $\mathbf{STPR}_i \subset \mathbf{STR}$

$\mathbf{SCOMP}_s$ Set of component(s) applicable to stream $s \in \mathbf{STR}$. Where $\mathbf{SCOMP}_s \subset \mathbf{COMP}$

$\mathbf{FPCO}_i$ Set of component(s) used for specifying the revenue/disposal cost of a final product $i \in \mathbf{PRODUCT}$.
Where $\mathbf{FPCO}_i \subset \mathbf{COMP}$

$\mathbf{AD}$ Subset of anaerobic digestion blocks $\mathbf{AD} \subset \mathbf{PROCESS}$

$\mathbf{DW}$ Subset of dewatering processes $\mathbf{DW} \subset \mathbf{PROCESS}$.

$\mathbf{CH}_i$ Set of matching a certain chemical conditioning stream s $\in \mathbf{CHEM}$ to a corresponding dewatering process $i \in \mathbf{DW}$.

$\mathbf{REVP}$ Subset of revenue-generating products $\mathbf{REVP} \subset \mathbf{PRODUCT}$

$\mathbf{DISP}$ Subset of cost-incurring products to be disposed $\mathbf{DISP} \subset \mathbf{PRODUCT}$

C. Parameters

CAP_i Maximum processing capacity of a certain process $i \in \mathbf{PROCESS}$ in tDS/day.

BCC_i Base (reference) capital cost of process $i \in \mathbf{PROCESS}$ in \$ (USD 2019)

BQ_i Base (reference) processing capacity of process $i \in \mathbf{PROCESS}$ used in capital cost calculation.

α_i Economies of scale exponent of process $i \in \mathbf{PROCESS}$.

POC_i Operating cost parameter for a certain process $i \in \mathbf{PROCESS}$.

DPY Days of operation per year

$FTHS$ Flowrate of thickened sludge to be processed in tonnes of dry solids per day

$FPVS$ Feed volatile solids mass percentage of total dry solids flowrate

$FPASH$ Ash mass percentage of dry solids

$PDS_{\boldsymbol{THS}}$	Dry solids mass percentage of total sludge flowrate
$VSD_i, i \in \mathbf{AD}$	Volatile solids destruction percentage
$Y_i^{\boldsymbol{E}}, i \in \mathbf{AD}$	Yield of net electricity per tonne dry volatile solids destructed
DR^{s}	Dosage rate of conditioning chemical stream s ∈ **CHEM.**
PDS_i	Percentage of total dry solids in dewatering process $i \in$ **DW.**
$PDS_{\boldsymbol{TD}}$	Percentage of total dry solids from thermal drying.
$LHV_{\boldsymbol{VS}}$	Lower heating value parameter (coefficient) for sludge.
$\lambda_{\boldsymbol{W}}$	Latent heat of vaporization of water.
HLF	Heat Loss Factor in the incinerator.
η_R	Efficiency of Rankine cycle.
CF_{MJ2kWh}	Conversion factor of MJ to kWh.
$YF_{\boldsymbol{GN}}^{\boldsymbol{E}}$	Yield of net electricity in kWh per tonne dry volatile solids fed to the gasifier.
$YF_{\boldsymbol{SCO}}^{\boldsymbol{E}}$	Yield of net electricity per tonne dry volatile solids fed to the SCWO block
$YF_{\boldsymbol{SCG}}^{\boldsymbol{H2}}$	Yield of hydrogen per tonne dry volatile solids fed to the SCWG block
AF	Annualized capital charge ratio
d	Interest/discount rate
n	Number of years of the project life
SP_i	Price of selling of a final product $i \in$ **REVP**.
DC_i	Disposal cost of a final product $i \in$ **DISP**.

D. Variables

$\boldsymbol{FI}_i^{\mathrm{s,c}}$	Total inlet flowrate of a component c ∈ **COMP** within a process stream s ∈ **STR** into process $i \in$ **PROCESS**.

$\boldsymbol{FO_i^{s,c}}$	Total outlet flowrate of a component c ∈ **COMP** within a process stream s ∈ **STR** out of process i ∈ **PROCESS**.
$\boldsymbol{X_{i,j}^{s,c}}$	Flowrate of a component c ∈ **COMP** within a process stream s ∈ **STR** going from any block i ∈ **I** to another block j ∈ **I**.
$\boldsymbol{SF_{i,j}^{s}}$	Split factor of a process stream s ∈ **STR** going from any block i ∈ **I** to another block j ∈ **I**.
$\boldsymbol{z_i}$	Binary variable that dictates whether a certain process i ∈ **PROCESS** exists or not. $\boldsymbol{z_i} \in \{0,1\}$
$\boldsymbol{CC_i}$	Capital cost of a certain process i ∈ **PROCESS** in $ (USD 2019)
$\boldsymbol{OC_i}$	Operating cost of a certain process i ∈ **PROCESS** in $/yr (USD 2019).
$\boldsymbol{CH_i^{s}}$	Flowrate of conditioning chemical s ∈ **CHEM** to a certain dewatering technology i ∈ **DW**
$\boldsymbol{FWE_{TD}}$	Total flowrate of water evaporated in the thermal dryer
$\boldsymbol{H_{INC}^{VS}}$	Heat flow of volatile solids entering incineration block
$\boldsymbol{H_{INC}^{W}}$	Heat required to evaporate moisture in sludge entering incineration block
$\boldsymbol{H_{INC}}$	Net heat recovered from incineration
$\boldsymbol{NETCOST}$	Objective function variable to be minimized representing the net production cost of the chosen pathway
$\boldsymbol{TACC}$	Total annualized capital costs of the chosen processes in the optimal pathway.
$\boldsymbol{TOC}$	Total annualized operating costs of the chosen processes in the optimal pathway.
$\boldsymbol{TADC}$	Total annual disposal costs from the disposal of final byproducts.
$\boldsymbol{TREV}$	Total revenues from selling of final products.
$\boldsymbol{FPI_i}$	Total flowrate of a final product i ∈ **PRODUCT**

Chapter 1
Introduction

1.1 Motivation

Wastewater treatment plants (WWTPs) have been a crucial element of maintaining the health and environment of modern societies. However, these facilities require a significant amount of energy and operational costs. It was estimated that WWTPs account for 3% of the total electricity consumption in the United States [1]. The treatment and handling of sewage sludge, which is the solids byproduct of WWTPs, accounts for approximately 30% of this electricity consumption [2] and 50% of the annual operating costs of a WWTP [3]. In addition, 73% of the treated sludge is eventually either landfilled or sent for land application [4], which are practices gaining less social and legislative support with more stringent disposal requirements being imposed. Thus, the need for more cost-effective, energy-efficient, and sustainable methods of sludge handling is increasingly important than ever.

In the past decade and coinciding with the efforts to combat global warming and climate change, there has been a paradigm shift taking place towards sludge. It shifted from being perceived only as waste and burden to society and the environment, to being rather looked at as a useful resource of materials and renewable energy. Several studies in the literature [5]–[9] reviewed available and potential technologies for energy recovery from sewage sludge in the form of electricity, heat, and/or fuels. These energy products can help in offsetting the energy consumption of the wastewater treatment facilities and thus reducing their carbon footprints as well as generating a revenue stream from products that can be sold in the market. Yet, there have been few efforts put into developing frameworks that quantitively compare those sludge-to-energy alternatives from an economic perspective.

On the other hand, for relatively similar feedstock materials such as biomass, microalgae, and municipal solids wastes, superstructure optimization approaches have been widely used for that comparative purpose of the relevant technologies to those feedstocks [10]–[16]. Therefore, the purpose of this research is to first provide the reader with an overview of a set of the most promising sludge-to-energy conversion technologies. Afterward, a mathematical model will be developed using a superstructure optimization-based approach that can be used as a decision-making support tool. This proposed approach should be useful for both researchers in the field as well as stakeholders in municipalities looking forward to putting master plans and strategies for biosolids handling in a sustainable future.

1.2 Thesis Outline

The thesis is organized as follows:

- **Chapter 2** encompasses necessary background information for the reader about sludge sources and characterization. It also provides an overview of the selected sludge-to-energy technologies that are going to be compared namely anaerobic digestion, pyrolysis, gasification, incineration, supercritical water oxidation, supercritical water gasification as well as the corresponding dewatering and drying methods for each technology. The key points covered for each technology include process description, reaction mechanisms, process conditions, and other factors impacting products yields.
- **Chapter 3** includes a literature review covering various themes like studies reviewing sludge-to-energy technologies, research on decision-making frameworks and methodologies for sludge-to-energy, sludge management optimization models, and finally waste-to-energy optimization models. The chapter concludes by identifying a research gap in the literature reviewed that aligns with the research objectives of this study.
- **Chapter 4** explains the methodology of this research and the steps followed to accomplish its goals. The mathematical formulation of the superstructure optimization problem is presented together with the basis of a case study utilized to demonstrate the applicability of the proposed mathematical model.
- **Chapter 5** shows the results of the case study including the optimal pathway and economic indicators. The uncertainty of case study parameters values is assessed using sensitivity analysis, the results of which are also presented in this chapter along with additional runs for technologies that were not selected in any scenario.
- Finally, **Chapter 6** concludes the whole thesis highlighting key findings and results. It also alludes to directions for future research that can complement and build on the work done in this study.

Chapter 2
Background Information

2.1 Sludge Characterization

Sewage sludge is composed of a complex series of microorganisms, organic and inorganic solid compounds (total solids) that coexist in water heterogeneously. The organic compounds, commonly called volatile solids (VS), originate from several sources like faecal material, plants, paper, and oils. They contain a variety of complex molecular structures from polysaccharides, lipids, proteins, and peptides to plant macromolecules (with both aliphatic and phenolic structures; examples of the first are cutins or suberins, and of the second are lignins or tannins), and micropollutant organic compounds like dibenzofurans and polycyclic aromatic hydrocarbons (PAHs) [17]. The energy recovery potential in the sewage sludge is highly dependent on the amount of VS present in the sludge (i.e. the higher the percentage of volatile solids, the higher the energy content of the sludge) [18]. The inorganic compounds, also referred to as ash, are mainly composed of minerals like silica (quartz), calcites, or microclines. Trace amounts of heavy metals are also present in sewage sludge, examples are Chromium, Copper, Nickel, Zinc, Mercury, Cadmium, and lead [19]. Finally, nutrients in the form of nitrogen, potassium (potash), and phosphorus are found in the sludge and are one of the main criteria upon which the suitability of the treated sludge for usage as a fertilizer or soil conditioner depends.

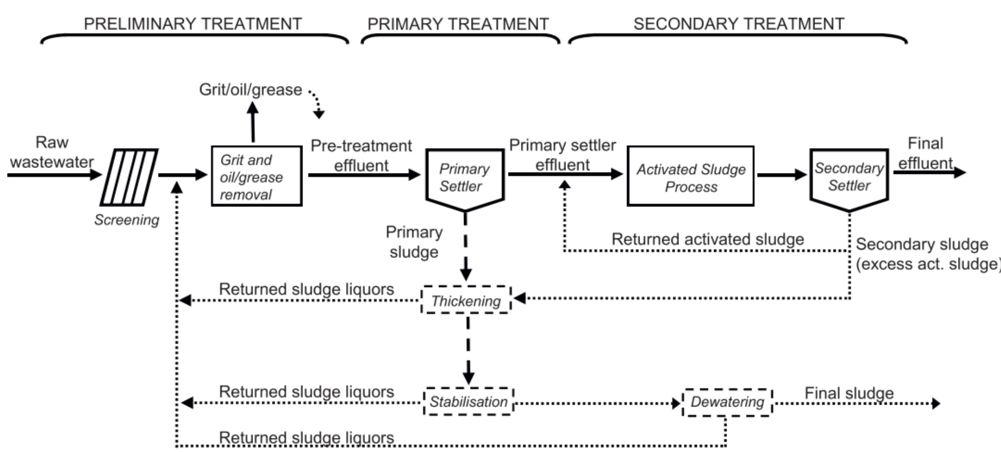


Figure 1 - Sludge production in a typical WWTP [20]

The sludge is usually divided into two types, primary sludge, and secondary sludge, depending on their source. Figure 1 shows a schematic for sources of sludge in a conventional WWTP. Mechanical wastewater treatment processes like screening, grit removal, and sedimentation are the source of primary sludge. Primary sludge is characterized by a higher percentage of volatile solids and a moisture content between 93% to 99.5%. On the other hand, secondary sludge is the by-product of secondary wastewater treatment (WWT) processes which are typically biological ones. Activated sludge treatment method is one of the most popular amongst secondary WWT, the excess sludge produced from it is referred to as waste activated sludge (WAS), thus the two terms: secondary sludge and WAS are often used interchangeably. Microbial cells are the main component of secondary sludges, they consist of complex polymeric organic compounds. The solids concentration in secondary sludge varies depending on the treatment process, typical ranges are between 0.8% and 1.2% which is significantly lower than primary sludge [21]. Typical ranges of different characteristics of both sludge types are listed in Table 1.

Table 1 - Characteristics of Primary Sludge and WAS [21]

Parameter	**Primary Sludge**	**WAS**
Total dry solids (DS) %	5 – 9	0.8 – 1.2
Volatile Solids VS (%DS)	60 – 80	59 – 68
Nitrogen (%DS)	1.5 – 4	2.4 – 5.0
Phosphorus (%DS)	0.8 – 0.28	0.5 -0.7
Potash [K_2O] (%tDS)	0 – 1	0.5 -0.7
Cellulose (%tDS)	8 – 15	7 – 9.7
Iron [Fe] (g/kg DS)	2 – 4	-
Silica [SiO_2] (%DS)	15 – 20	-
pH	5.0 – 8.0	6.5 – 8.0
Grease and Fats (%DS)	7 – 35	5 – 12
Protein (%DS)	20 – 30	32 – 41
Alkalinity (mg/L as $CaCO_3$)	500 – 1500	580 – 1100
Organic acids (mg/L as acetate)	200 – 2000	1100 – 1700
Energy Content (kJ/kg DS)	23,000 – 29,000	19,000 – 23,000

2.2 Anaerobic Digestion

Anaerobic digestion is the most common process to stabilize sewage sludge in today's market [22]. In this process, a portion of the biodegradable organic compounds in the sludge is decomposed in an oxygen-free environment to a methane-rich gaseous mixture called "biogas" [17]. The unconverted portion of organic compounds in the digester together with the inorganic compounds and moisture exit the process and are named "digested sludge" or "digestate".

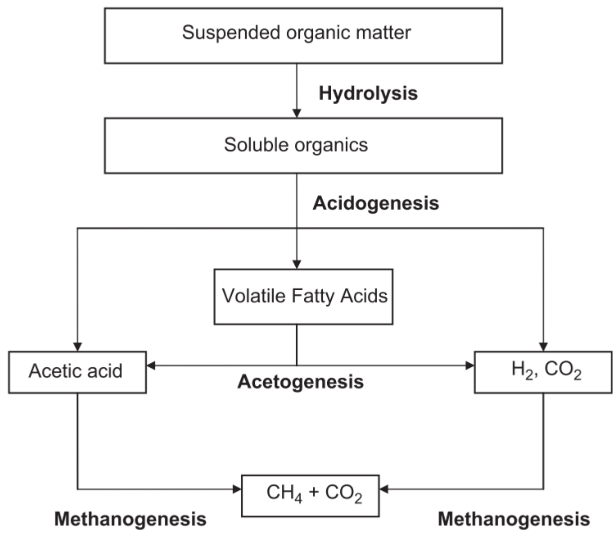


Figure 2 - Anaerobic Digestion Reaction Steps [23]

The digestion process takes place in a series of complex biochemical reactions that can be summarized in four phases as visualized in Figure 2. Hydrolysis converts insoluble and high molecular weight organic compounds such as polysaccharides, proteins, and lipids into soluble amino and fatty acids. Those soluble compounds from hydrolysis are additionally split to form volatile fatty acids in the acidogenesis step. Acetogenesis is the step in which the organic acids and alcohols generated in acidogenesis are converted to acetic acid together with hydrogen and carbon dioxide. Finally, the methanogenesis step is where methane gas is predominantly produced by two different methanogenic groups of bacteria, one of them decomposes acetate to CH_4 and CO_2 and the other group utilizes H_2 as an electron donor and CO_2 as an acceptor to produce CH_4 [23]. The hydrolysis step is generally deemed as the rate-limiting one.

Anaerobic digestion is sensitive to the feed characteristics and operating conditions such as pH and temperature for the bacteria to perform efficiently [20]. Digesters are typically operated at either mesophilic temperatures ranging from 30 °C to 38 °C or thermophilic temperatures between 50 °C and

57 °C. The minimum solids retention time (SRT) that is required to achieve a certain level of volatile solids destruction (VSD) highly depends on the temperature at which the sludge operates, where higher temperatures lead to lower min required SRT and thus leads to smaller digester volumes. However, this comes at a higher heating requirement expense and lower process stability when compared to mesophilic anaerobic digestion [21], [24]. The SRT resembles the time required to complete the reaction and it ranges between 18-25 days at mesophilic conditions, which is considered a big limitation of the process [25]. This reaction time is significantly longer than all the other treatment methods that will be discussed later in this chapter which have reaction times in the magnitude of minutes or seconds.

The latent energy content in the destructed portion of volatile solids can be recovered from the produced biogas. The yield range of biogas from primary and activated sludge is 362 – 612 m^3/tonneVS (tVS) and 275 – 380 m^3/tVS respectively. The biogas consists of 60 – 70% by volume of methane and 30 – 40% of carbon dioxide together with traces of hydrogen, hydrogen sulphide, nitrogen, and water vapour. It can be used as an energy source to produce both heat and/or electricity in combined heat and power (CHP) units. It can also be used in electricity production using engines, turbines, fuel cells, and it can alternatively be utilized as a gas fuel for vehicles [17]. Around 80% of the total operating cost in WWTPs is accounted for the cost of electricity, half of that cost can be covered by utilizing the biogas produced from anaerobic digestion of the produced sludge [17].

A pretreatment step of the sewage sludge being fed to the digester can be added to further enhance the performance of conventional digestion methods. Depending on the pretreatment method, the enhancement can be in the form of increased biogas yields, increased destruction rate of volatile solids, or increases in the solids loading rate. The pretreatment methods can be categorized as thermal, chemical, physical, or electrical [21]. An overview of the different methods under each category and relevant studies on them is given in [23]. Thermal hydrolysis pretreatment (THP) has received special attention in the literature that eventually led to commercialized applications such as Cambi™ and Exelys™ technologies [26]. Thus, the combination of mesophilic anaerobic digestion (MAD) and THP will be considered as an advanced alternative in the biological treatment step of sewage sludge in our research problem.

2.3 Incineration

Incineration is a process in which waste combustion takes place in a controlled manner producing flue gas, ash, and heat that can be recovered. Incineration and combustion of sewage sludge are sometimes used interchangeably, however, it needs to be noted that there is a subtle difference between both terms. Combustion is a more general term that refers to a thermochemical exothermic reaction between excess oxygen and organic material of a fuel that is completely oxidized to CO_2 and H_2O at high temperatures. Incineration on the other hand is a special case of combustion where the combustible material originates from a waste that needs to be disposed of. The main purpose of combustion is the energy recovery from the fuel in the form of heat that can then be used in steam generation which in turn can produce electricity upon passing through steam turbines, while incineration's main purpose is the destruction of the harmful material in the waste and reducing its volume upon disposal [20]. For the purpose of our work, where energy recovery is of the main interest, incineration and combustion of sewage sludge will refer to the same concept. Sewage sludge combustion takes place in six different stages that are well explained in [27] and are ordered as follows: 1) drying, 2) devolatilization and auto-gasification, 3) combustion of volatiles, 4) ash melting, 5) combustion of char, and finally 6) ash agglomeration.

The ash produced from sewage sludge incineration, accounting for around 30 wt% of the total dry solids of the sludge, requires adequate disposal. Depending on the heavy metals content, it may be sent to landfills, used for agricultural purposes, or as a raw material for building materials such as concrete [28]. The flue gas product exits from the furnace at very high temperatures between 850-1300 °C [20]. It is composed of combustion products like CO_2 and H_2O together with excess oxygen and trace amounts of harmful gaseous products originating from sulphur, nitrogen, dioxins, furans, chlorine, etc. that are present in the sludge [29]. The heat associated with the flue gases can be recovered in heat exchangers for preheating of combustion air, sludge drying, or steam production [20]. The amount of energy recovered has a strong dependence on the quantity of moisture associated with the sludge, efficiency of drying and dewatering equipment, and percentage of volatile solids in the sludge dry solids [30].

A typical sludge incineration system, as shown in Figure 3, includes a sludge feeding system, dewatering equipment (more about dewatering in section 2.7), an incinerator, an ash handling system, heat exchangers and/or boilers (optional), and air pollution control devices [31]. There are several types of incinerators available in the market, the most common ones are the multiple hearth furnaces (MHF) in older plants and fluidized bed furnaces (FBF) in newer ones. The latter has fewer problems with emissions due to the fact that sludge combustion occurs in a more uniform manner compared to MHF [31]. The flue gas cleaning equipment are one of the main factors that significantly increase the cost of incineration units compared to other stabilization methods [30].

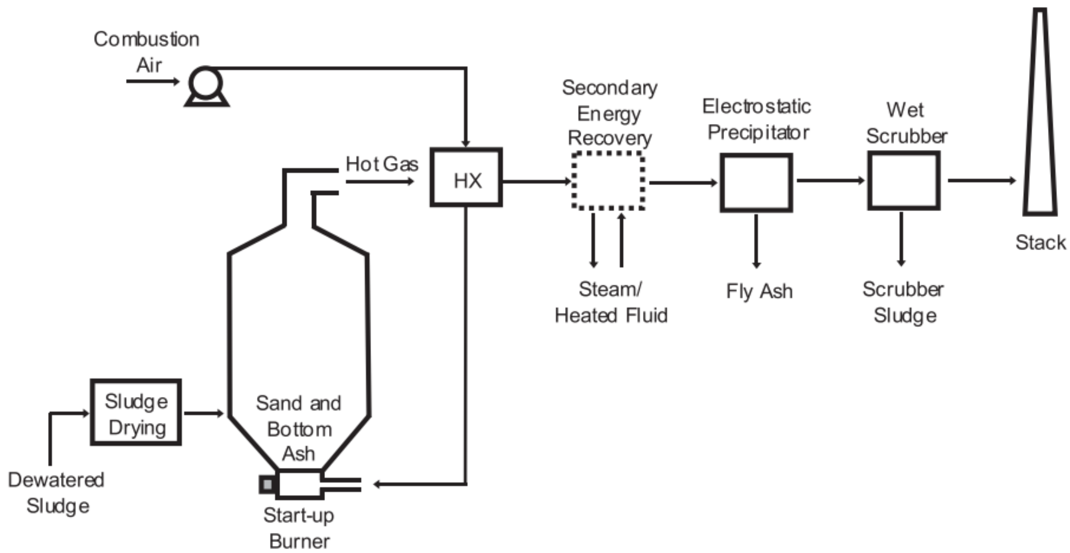


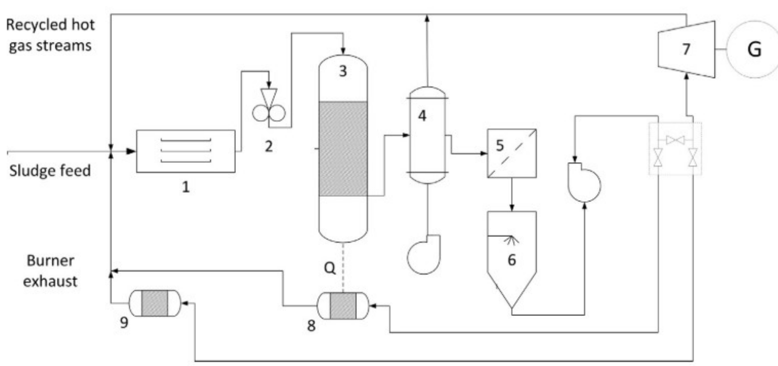
Figure 3 - Process flow diagram of a typical sludge incineration system [20]

2.4 Gasification

Gasification is another thermochemical conversion process in which the organic components of sludge are transformed in a net reducing environment to a combustible gas called syngas while the remaining sludge constituents are converted to ash [32]. There are lots of similarities between gasification and combustion but they mainly differ in the lower requirement of sludge moisture content fed to the gasifier (below 15 wt%) and that oxidants are present in amounts below the stoichiometric quantities required for complete combustion or oxidation [25]. Syngas or synthesis gas is a mixture that consists of mainly hydrogen (8.89-11.17 vol%), carbon monoxide (6.28-10.77 vol%), lower percentages of methane (1.26-2.09 vol%) and C2s (0.75-1.2 vol%), along with CO_2 and the gasification medium [33]. The gasification medium, also called the gasifying agent, is the fluid which reacts with the sludge carbonaceous components to partially oxidize them to syngas. Typically, air with oxygen amounts of 20-40% less than that required for complete combustion is used as gasifying agent. Nevertheless, the following media has been also studied and used in sludge gasification: pure oxygen, steam, steam-air mixture, steam-O_2, steam-CO_2, and pure CO_2 as reported in the review study [20]. The gasification medium has a significant impact on the composition and accordingly the heating value of the produced syngas with ranges from 4 to 12 MJ/Nm^3 where the highest values are obtained from gasification with pure oxygen [25]. Steam gasification increases the yield of H_2 in the syngas mixture compared to CO which can be attributed to both the reforming of methane and the water-gas shift reaction promoted by steam. Higher H_2/CO ratios correspond to higher syngas calorific values as well [34].

A detailed explanation of gasification reactions can be found in [20]; the reactions take place in 4 operation regions or zones: 1) drying zone (70 – 200 °C), 2) devolatilization/pyrolysis zone (350 – 600 °C), 3) oxidation zone (exothermic at around 1100 °C), and finally 4) a gasification/reduction zone. The extent of each reaction depends on several factors such as the gasification medium, reaction conditions, sludge composition, use of catalysts, gasifier type [20]. Several gasifier reactor types and configurations are available for sludge gasification including fixed-bed updraft gasifier, fixed-bed down-draft gasifier, and fluidized-bed gasifiers [20]. For comprehensive descriptions and comparisons of each type, the reader is referred to [35] and [36]. The main difference is lying in the contact method between sludge and the gasifying agent which will impact the location of each of the 4 operating zones previously described. The type of reactor has also an impact on the amount of pollutants and tar associated with the product syngas which can negatively affect the process efficiency [25].

The syngas product is the energy carrier of the latent energy content that was originally present in the sewage sludge. This energy can be recovered in different methods, the most common will be via direct combustion in a combined cycle gas turbine which generates heat and electricity simultaneously. Syngas can also be sent to be further upgraded to chemicals or liquid fuels using the Fisher-Tropsch gas-to-liquid (GTL) synthesis process [25]. Regardless of the final energy recovery utilization method of the syngas, it requires a cleaning step first for tar and residual solids (dust, mercury, etc) removal before its end use [37]. The other product of gasification, which is the residual ash, can be either disposed to landfills or have beneficial uses as a component for construction materials or in agricultural soil amendment products depending on its composition and heavy metals content [25]. A proposed process flowsheet for sludge gasification with energy recovery was presented in the techno-economic study done by Lumley et al. [38] and is shown in Figure 4 below.



System flowsheet. 1: dryer, 2: briquetter, 3: gasifier, 4: syngas cooler, 5: filter, 6: wet scrubber, 7: engine generator, 8: gasifier heating burner, 9: dryer heating burner, Q: heat supplied to gasifier from burner.

Figure 4 - Process flowsheet of sludge gasification with energy recovery [38]

2.5 Pyrolysis

Pyrolysis is a thermochemical process in which the organic components of the sludge are destructed at temperatures between 300 °C to 700 °C in an oxygen-free environment [20]. Unlike combustion, which is an exothermic process, pyrolysis requires a significant amount of heat (in the range of 100 MJ/tDS) for its reactions to occur [39]. It also has a much lower moisture content tolerance to the sludge that enters the reactor (<10 wt%) and thus requires higher drying energy [25]. The first step of the process takes place when the sludge is heated to temperatures in the range of 100-200 °C where the remaining moisture associated with the sludge is evaporated and volatile gaseous products start to form, leaving a solid residue with non-volatiles referred to as char. These products are the result of several bond-breaking and forming reactions and are called primary pyrolysis. This is the same initial step in other thermochemical processes discussed as combustion and gasification [40]. With further heating, the next step, called secondary pyrolysis, takes place at temperatures close to 600 °C where the volatile gaseous products undergo further decomposition into simpler low molecular weight gases and stable aromatic compounds. The vapour product is then sent for cooling and is separated into a liquid product called bio-oil and non-condensable gases (syngas). Bio-oil is a complex mixture of different compounds comprised of mainly four groups: 1) Aliphatic and/or aromatic hydrocarbons, 2) Oxygen-containing hydrocarbons such as ketones, phenols, sugars, alcohols, and acids, 3) Nitrogen-containing compounds such as pyridine, pyrazine, and amines, and 4) an aqueous phase (water) [40].

From the discussion above, it can be summarized that the pyrolysis process has three products: syngas, bio-oil, and bio-char. Syed-Hassan et. al [20] stated the main factors that affect the yield of each of those products and their properties to be: pressure, temperature, sludge composition, sludge particle size, solid feed rate, use of catalysts, and most importantly residence time. Depending on the residence time of sludge in the reactor and the heating rate, pyrolysis can be categorized into three different types: a) Slow Pyrolysis, also known as carbonization, which takes place at long residence times, in the range of hours or even days, and is mainly targeting maximizing the bio-char yield; b) Fast Pyrolysis conducted at short residence times 0.5 – 10 seconds (typically less than 2 seconds), and high heating rates 10-200 °C/s). Flash pyrolysis also occurs at short residence times and high heating rates at values of less than 2 seconds and 103–104 °C/s respectively [41]. Both fast and flash pyrolysis processes target maximizing the yield of bio-oil product where fast pyrolysis is more commonly studied [25]. Fast pyrolysis has three main types of available technologies: fluidized-bed pyrolysis, ablative pyrolysis, vacuum pyrolysis, and circulating fluidized-bed pyrolysis. The most popular configuration is that of fluidized-bed because of their scaling-up potentials and relatively easier operation [42].

Bio-oil production receives special attention for applications concerned with energy recovery since it can be easily stored and transported. It also has a heating value of up to 33 MJ/kg [20], this energy can be recovered whether by using the bio-oil directly as a fuel or by further upgrading and refining to higher value transport fuels [19]. It can also be reformed to produce syngas or utilized as feed material for the production of chemicals [41]. When bio-oil is the main product of interest, syngas and biochar are rather considered as by-products regardless of their notable energy content [20]. They can be directly combusted to supply the heat required for pyrolysis reaction, however, biochar is considered unattractive due to the high ash content when produced from sewage sludge. Alternative uses for biochar are in adsorption and/or agricultural applications [25]. Figure 5 below shows a graphical representation of sludge pyrolysis to energy process flow diagram.

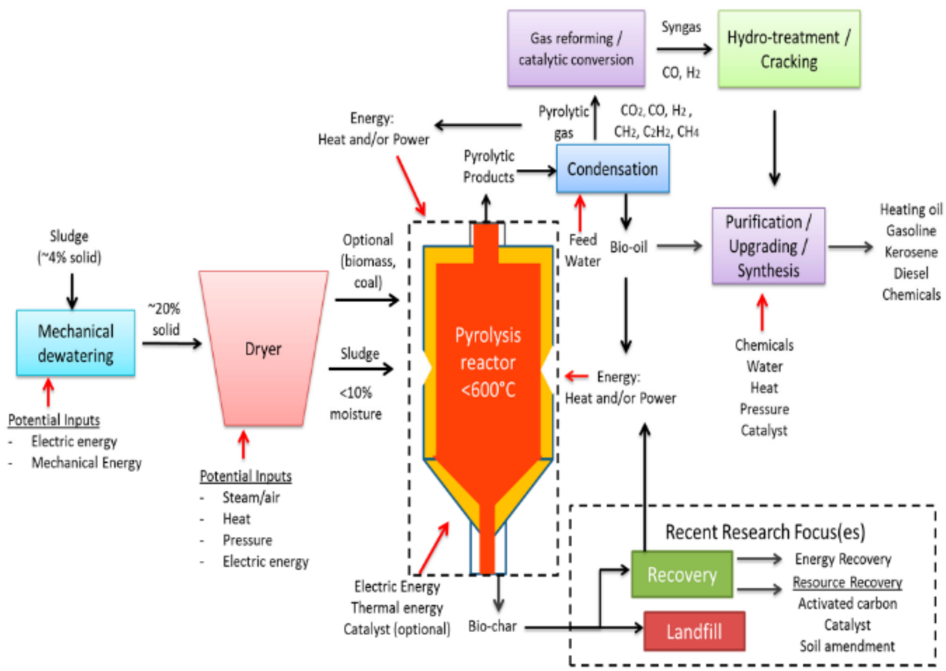


Figure 5 - Process Flow Diagram of Sludge Pyrolysis [25]

2.6 Supercritical Water Treatment Methods

The thermochemical sludge treatment methods discussed so far, i.e., incineration, gasification, and pyrolysis, all require a drying step before the sludge processing into them. The fact that raw and/or digested sludges have a significantly high moisture content, makes those processing routes rather more capital and energy intensive. An innovative way to stabilize sludge while eliminating the need for a pre-drying step is to treat it in the supercritical water (SCW) phase [43]. As shown in the phase diagram in Figure 6, supercritical water is a phase that takes place when critical temperature and pressure values of water are exceeded (374 °C and 22.1 Bar respectively) [43]. At such state, one cannot distinguish between water in its liquid and vapour phase (steam) and water has unique properties. In this section, two SCW treatment methods will be briefly discussed namely supercritical water oxidation (SCWO) and supercritical water gasification (SCWG).

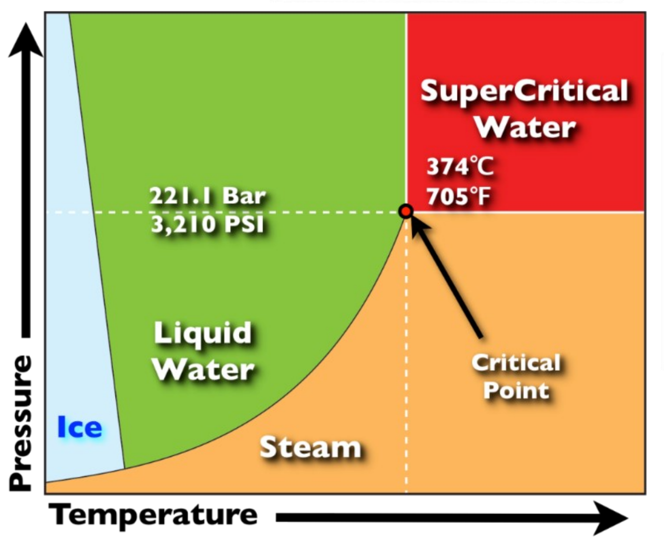


Figure 6 - Phases of Water [44]

2.6.1 Supercritical Water Oxidation (SCWO)

SCWO occurs at high temperatures and pressures (around 600 °C and 25 Bar), conditions that are well suited for the disintegration of sewage sludge [17]. Much higher oxidation rates are observed in supercritical conditions compared to subcritical ones, which can aid in the complete destruction of organic constituents of the sludge [31]. Organic compounds are composed of mainly carbon, hydrogen, nitrogen, sulphur, and phosphorus which are oxidized to CO_2. H_2O, N_2, SO_4^{2-}, and PO_4^{3-} respectively, while heavy metals get oxidized to their respective oxides [17]. Most of the oxidation reactions occur at a conversion rate of 99.9% and reaction times of 30 seconds or less at a temperature of 600°C which results in relatively small reactor dimensions [45]. Another advantage to SCWO compared to incineration is the simple treatment required for the off-gas released which was a major cost in incineration plants [17]. Since SCWO is an exothermic reaction, energy recovery can be achieved either from heat exchange with the reactor vessel directly or with its effluent product to produce steam [17]. A schematic for a commercially available sludge SCWO technology called AquaCritox® currently licensed by SCFI [46] is shown in Figure 7.

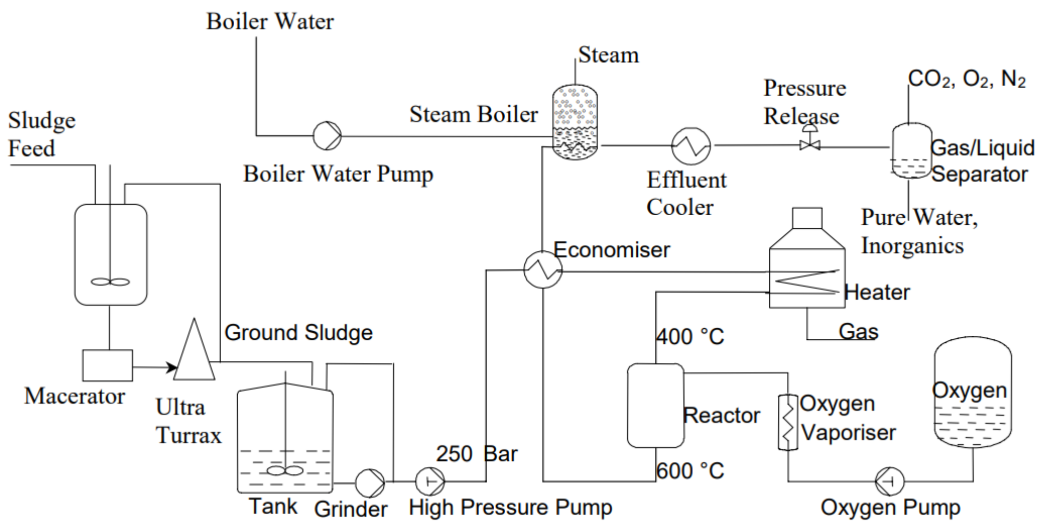


Figure 7 – AquaCritox® Technology Principal Flowsheet [47]

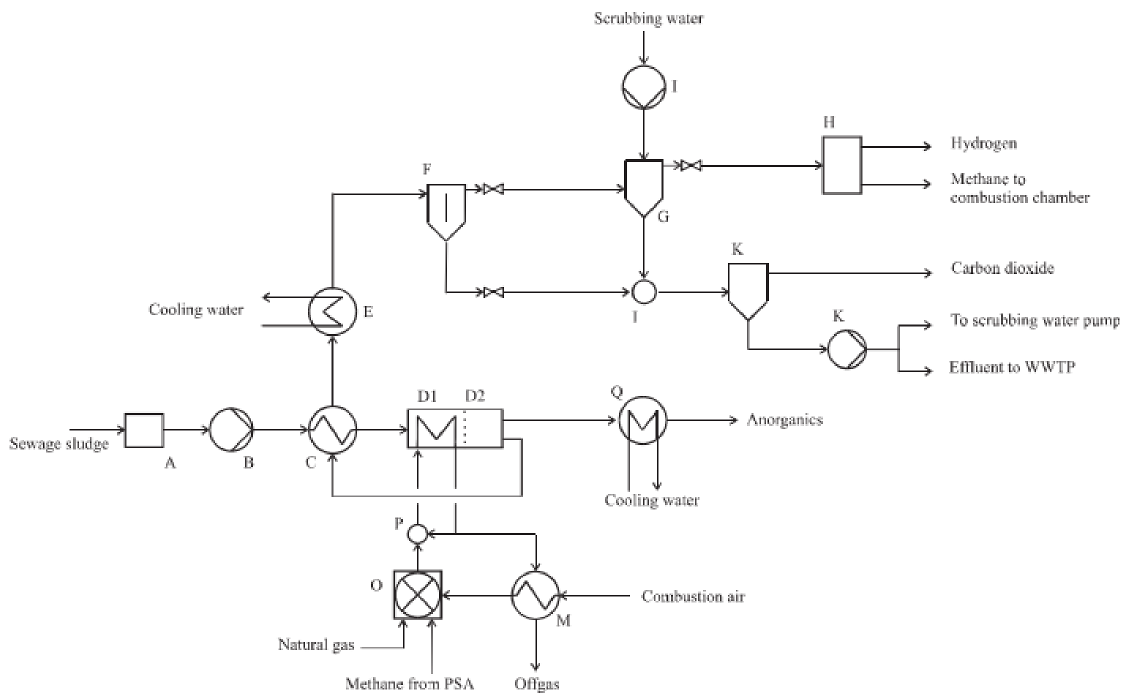
2.6.2 Supercritical Water Gasification (SCWG)

Similar to conventional gasification (explained in section 2.4), SCWG decomposes the organic constituents of the sewage sludge into a gaseous mixture called syngas, however, the composition of the syngas from SCWG is much richer in hydrogen which makes this technology especially attractive. Supercritical water gasification (SCWG) of sewage sludge was studied in several research works for the purpose of hydrogen production. This technology has not been implemented yet at full scale but shows great potential for future adoption. Some of the main advantages of SCWG of biomass in general, which apply to sewage sludge as well, were summarized in [48] as follows:

- No need for prior drying of the feedstock to the SCWG reactor, conversely, the moisture content of the feed is necessary for the reaction.

- Higher yield of H_2 compared to CO (less than 1% by volume) in the syngas product whereas in dry gasification processes CO is the main constituent of syngas and an extra water-gas shift process is required to achieve such high H_2:CO ratios.
- Lower amounts of coke and tar formation.
- Salts remain in the aqueous solution which avoids corrosion problems during treatment of the produced gas.

Depending on the production scale, the hydrogen product from SCWG can be sold in the market as fuel for H_2 fuel cells, used in refineries, or other industrial uses (ammonia, methanol, etc) [49]. A proposed process flow diagram for sewage sludge SCWG for hydrogen production was presented in the economic analysis study by Gasafi et al. [48] and is shown in Figure 8 below.



Flowchart of supercritical water gasification: A, conditioning unit; B, high-pressure pump; C, heat exchanger; D1, heat exchanger; D2, reactor; E, heat exchanger; F, gas–liquid separator; G, scrubber; H, pressure-swing adsorption (PSA); I, high-pressure pump; J, mixing unit; K, expansion unit; L, sewage water pump; M, heat exchanger; O, combustion chamber; P, mixing unit; Q, cooling screw.

Figure 8 – Flowchart of sludge SCWG for hydrogen production [48]

2.7 Dewatering and Drying

The water content removal is an essential step in any sludge treatment plant to achieve volume reduction of the stabilized product for further disposal or treatment, such reduction has a significant effect on the transportation and/or energy costs. There are four different categories of water/moisture present in sewage sludge: free water, adsorbed water, capillary water, and cellular water. Free water is the easiest of which to remove and is achieved by simple flotation or gravitation methods. Gravity thickeners are an example of such water removal unit operations where an influent sludge of 2% dry solids (DS) exits at a concentration close to 5% DS, which results in a volume reduction of up to 60%. Adsorbed and capillary waters on the other hand required much higher forces compared to free water. These higher forces can be accomplished mechanically by dewatering equipment like centrifuges or filter presses (more on that later in the section), or chemically by the employment of flocculants. A final product called "cake" or "dewatered sludge" with a concentration greater than 30% DS can be achieved. This product has a semi-solid appearance and compatibility with belt conveyer transfer or manipulation of spades. The removal of the three categories of water discussed so far can result in a volume reduction in the range of 90-95% to an influent originally at 2% DS. The last category, cellular water, is the hardest to remove and requires even higher forces that can only be achieved thermally. Thermal dryers can produce a granular product with up to 95% DS in an efficient manner [50].

The water removal steps which lie within the scope of our study are dewatering and thermal drying. Prior to sludge dewatering, an important pretreatment is required referred to as sludge conditioning. This step is crucial in impacting the efficiency and ease of sludge dewatering and can be achieved via different methods: thermal pretreatment or the use of organic and/or inorganic chemicals. The most popular chemical conditioners are inorganic lime and ferric chloride and organic polymers. Chemical type and dosage rates depend on the sludge characteristics and dewatering method/equipment type. The most common dewatering methods are belt presses, centrifuges, vacuum filters, plate or diaphragm filter presses and exclusively for digested sludges: sludge lagoons and drying beds. The performance of each method in terms of outlet percentage of dry solids for different types of sludges is summarized in Figure 9 below. Typical ranges of dewatering performance for a mixture of 70% WAS and 30% primary sludge (both digested) are: solid bowl centrifuge (13-18% DS), vacuum filter (12-17% DS), belt filter (15-23% DS), and for recessed plate filter press (32-40% DS) [51].

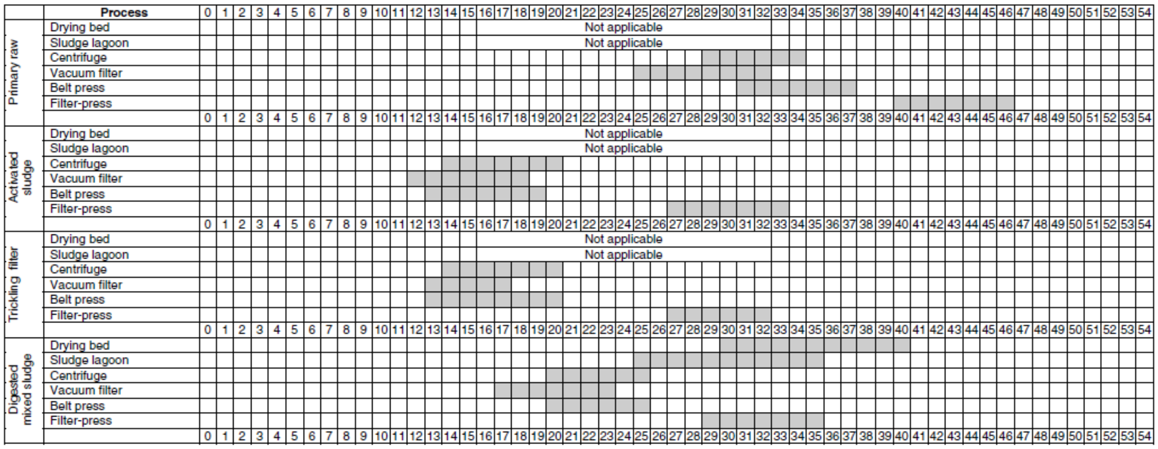


Figure 9 - Sludge Dewatering Methods Performance [50]

Thermal drying can be achieved either by direct or indirect methods, where the difference lies in whether the heating medium is in direct contact with the sludge or not. Direct drying methods are more commonly used. Examples of direct dryer technologies are rotary dryers, fluidized bed dryers, and belt dryers. One of the advantages of thermal drying is that it acts as both a further stabilization and volume reduction method of the sludge. The end product can be sold as Class A biosolids (pathogen-free) which can be sold for agricultural uses as a fertilizer. However, the high operating costs associated with drying are usually not offset by the revenues generated from selling the dried product [21]. Also, another problem associated with sludge drying is the potential production of odours and volatile organic compounds (VOCs) [52].

Chapter 3
Literature Review

3.1 Sludge-to-energy studies

There are several research papers that reviewed different sludge-to-energy technologies; Table 2 below maps various technologies with the corresponding research papers. It can be clearly observed that anaerobic digestion, incineration, gasification, and pyrolysis are the most reviewed and discussed technologies within the literature found.

Table 2 – Literature reviewing Sludge-to-energy technologies

AD	INC	PY	GASN	WAO	HTL	SCWO	SCWG	MFC	Ref.
✓	✓	✓	✓	✓	✓	✓			[5]
✓	✓	✓	✓	✓		✓			[6]
✓		✓							[22]
	✓	✓	✓						[34]
✓	✓		✓	✓	✓	✓	✓		[7]
	✓	✓	✓						[34], [20]
✓	✓	✓	✓					✓	[8]
✓	✓	✓	✓						[25], [53]
✓	✓	✓	✓				✓		[9]

AD: Anaerobic digestion; INC: Incineration; PY: pyrolysis; GASN: gasification; WAO: Wet air oxidation; HTL: Hydrothermal Liquefaction; SCWO: supercritical water oxidation; SCWG: supercritical water gasification; MFC: microbial fuel cell.

Studies [6], [7], [20], and [25] were purely review papers explaining fundamentals and state-of-the-art of the corresponding technologies and did not include overall comparisons between the various options. Conversely, some studies followed the explanation of the conversion technologies with some sort of comparative assessment using different methodologies. For instance, in study [5], based on the technology process descriptions and state of maturity in the industry, technologies were grouped into two groups: mature technologies and development-stage technologies; the study attributed more advantages to the first group over the second one. Study [22] quantitatively compared the energy efficiency of two pathways: pyrolysis only and AD followed by pyrolysis and reached the conclusion that the latter pathway is of better energy performance. A SWOT analysis was conducted for technologies reviewed in [34] based on the following criteria: solving sludge management problem, greenhouse gas (GHG) emissions, maturity of technology, and legislative aspect in Greece. The result of the comparative study was in favour of pyrolysis as the most sustainable pathway based on the criteria studied. In study [9], SWOT analysis methodology followed by Fuzzy Analytic Hierarchy Process (FAHP) was applied to the studied technologies in Turkey using similar criteria as those just mentioned in reference [34]. The result of the case study was choosing SCWG as the most favourable alternative. Finally, study [8] provided a qualitative comparison based on technological, social, environmental, and economic considerations of the explored options and concluded that coupling both anaerobic digestion with a thermochemical process like combustion or pyrolysis can be a promising way forward that balances the pros and cons of each group of technologies (i.e. biological and thermochemical).

A common feature between all the above-mentioned studies conducting comparisons is the lack of considering the economic aspect in a quantitative manner. This gap was addressed in the study by Mills et al. [54] by comparing the following five processing pathways: 1) MAD + CHP; 2) MAD + THP + CHP; 3) MAD + THP + bio-methane injection; 4) MAD + THP + CHP + drying; 5) MAD + THP + CHP + drying+ pyrolysis. The comparison took into consideration life cycle assessment (LCA) from both environmental and economic aspects in a quantitative manner. Pathways with drying of the product sludge had a better overall performance where the best results were obtained from the fourth pathway. Gasification and SCW methods were not considered in that study. In addition, the pyrolysis type was not mentioned (whether slow or fast pyrolysis, see section 2.5), and fast pyrolysis is more favourable in terms of energy recovery. Fast pyrolysis was not considered also in other comparative studies that looked at the energy efficiency of coupling MAD with pyrolysis [55], [56]. It needs to be noted that study [55] concluded that MAD has better energy and environmental performance compared to MAD followed by slow pyrolysis which is contrary to the hypothesis stated in the conclusions of study [8] about coupling both technologies. This might be explained by the fact that fast pyrolysis was not studied in [55].

3.2 Sludge-to-energy decision-making frameworks

There are significant efforts in developing decision-making support frameworks or tools that help in ranking different sludge-to-energy alternatives. Multi-criteria decision-making (MCDM) methodologies were applied to the problem of sludge management in studies [57] and [58]. The former study was based on traditional grey relational analysis (GRA) modified to allow for linguistic inputs while the latter study was based on Dempster-Shafer theory and fuzzy best-worst method. Both studies considered environmental, technological, social, and economic criteria. Linguistic values or scores were given for the various criteria evaluated in reference [57] which were then converted to grey numbers. On the other hand, quantitative values for environmental and economic parameters such as capital and operating costs were used in study [58], however, it was based on simple linear parameters that do not take into consideration economies of scale. Tang et al. [59] proposed another MCDM framework for prioritizing different sludge technologies using four different methodologies combined with triangular fuzzy numbers to deal with hybrid-data types. This work also contained a recent review of other related studies in the area of decision-making for sustainable sewage sludge management. Although MCDM tools can be useful, they are not flexible in assessing and synthesizing innovative combinations of various technologies at different capacities to maximize economic or environmental benefits (biorefinery concept). In addition, many of these tools rely on "experts' opinion" which might lead to more subjective or biased results. A more suitable approach to address those limitations would be to formulate optimization mathematical models for superstructures mapping the different alternatives. Typically, these optimization problems are modelled and solved by mixed-integer linear programming (MILP) or mixed-integer non-linear programming (MINLP) models.

3.3 Sludge Management Optimization Models

There were very few studies found in the literature that utilized MILP in solving a sludge management-related problem. A case study in [60] compared alternatives for thermal treatment of digested sludge in the region of Zurich in Switzerland. A multi-objective MILP was developed to find the optimal environmental performance of the following technologies: sludge mono-incineration, co-incineration with municipal solid waste (MSW), and co-processing for cement manufacturing. This study did not cover any energy recovery method other than incineration, and it also did not consider the economic performance and costs associated with the potential pathways. Another application was in article [61], where a stochastic multi-objective MILP model was utilized to compare different sludge utilization pathways namely: anaerobic digestion with thermal hydrolysis, lime stabilization, incineration, land application, and selling of Class-A biosolids in the market as a fertilizer. Also, several utilization paths for the produced biogas were considered like electricity production and upgrading to compressed natural gas (CNG). The economic performance in terms of capital and operating expenditure as well as revenue from valuable products were considered. Also, environmental performance in terms of CO_2 emissions and energy costs were considered. However, as with the case in study [60], only a few energy recovery technologies were included in the model.

The work done in [62] looked at the whole sludge supply chain in a certain region in north-western Europe considering the synergies between 241 WWTPs. A generic decision framework called OPTIMASS, originally created for optimizing biomass supply chains [63], was customized to fit the specific application of sewage sludge. However, only a limited number of energy recovery alternatives were included in the model with the following processing equipment/routes: thickening, dewatering, MAD, thermal drying, mono/co-incineration, and utilization in the cement industry. Another shortcoming of that study was the unavailability of the parameters used in the model due to privacy agreements. The final study reviewed in that theme is [64] where anaerobic digestion, hydrothermal liquefaction, and catalytic hydrothermal gasification pathways were compared using a multi-objective superstructure optimization methodology. The MILP model developed considered both economic and environmental aspects while CAPEX and OPEX were assumed to have linear relations. Although more technologies were assessed in that study in comparison to the former ones mentioned, the study still did not consider some of the most studied sludge-to-energy technologies that were discussed in Chapter 2 such as incineration, gasification, and pyrolysis.

3.4 Waste-to-energy Optimization Models

Aside from sewage sludge, there is much more available literature on the application of superstructure optimization or mixed-integer programming methodologies to find the optimal processing pathway for energy recovery from other types of wastes. The majority of those studies are related to the different types of MSW like plastics, metals, glass, and various other organic wastes (paper, textile, food waste, etc) and some examples are mentioned in this section. A fuzzy multi-objective superstructure optimization methodology with the aim of cost-minimizing while maximizing waste reduction and electricity generation was introduced in [65]. LP and MINLP (linearized to MILP) superstructure optimization models were proposed in studies [14] and [15] respectively with a single objective function of maximizing net profit for the selected technology pathway. The work done in [66] was not limited to only optimal technology selection, it also considered the complete supply chain of MSW including transportation between different cities. The objective function to be optimized in the MILP formulation of that study aimed at maximizing the economic benefit while considering environmental cost incurred because of CO_2 emissions. Another study [67] looked at supply chain optimization together with technology selection via a multi-objective MILP model. The multiple objectives were 1) minimizing economic and environmental costs and 2) minimizing the associated risks with the pathway chosen. The latter study also includes a comprehensive list of many of the work related to MSW optimization modelling frameworks.

Poultry litter is another type of waste that decision-making tools based on optimization mathematical models were applied to. The recent work of [16] and [68] studied the comparison of thermochemical valorisation pathways developing mixed-integer (non)linear fractional programming models. A parametric algorithm was proposed for linearizing the optimization models to a series of MILP problems to obtain solutions in a relatively less computationally intensive way. The first study aimed at just technology selection while maximizing return on investment (ROI). This objective function is the source of fractional non-linearity of the model due to the presence of a ratio of two linear equations. The second study looked at the comparison of two pyrolysis pathways, slow and fast pyrolysis, for the valorisation of poultry waste considering multiple objectives; the first being maximizing annualized profit per unit waste while the second is minimizing the equivalent CO_2 emissions from the chosen pathway. This study also considered optimizing the whole supply chain including the selection of the optimal location of pyrolysis facilities in relation to the waste sources taking into account transportation costs. The proposed methodology was applied to a case study for the poultry waste supply chain in the state of Georgia in the United States.

3.5 Research Gap

It can be concluded from the literature review above that there exists rich literature discussing several conventional and emerging technologies for converting sewage sludge to energy. Selecting the optimal process configuration and synergies between those various options is rather a complex task. There are studies that proposed decision-making frameworks that can help decision-makers relying on expert opinions to prioritize or rank the available alternatives. Superstructure optimization using mathematical programming models can aid in providing an objective decision-making support tool to quantitatively compare and/or synthesize pathways of sludge-to-energy conversion. This methodology is already applied to other types of wastes such as MSW and poultry waste. However, there is a research gap in applying such models to municipal sewage sludge, and the aim of this research is to contribute to this gap.

Chapter 4
Methodology

4.1 Overview

The approach proposed for tackling this research is outlined in Figure 10 below. The first step is to identify candidate technologies that have the ability to convert sewage sludge to energy products. This has been accomplished by the literature review and the background explanation given to each technology in chapters 2 and 3. The second step is to develop a superstructure mapping those various alternative technologies (further explained in the following section). Subsequently, a mathematical model formulation for the optimization problem, which is the main research contribution, is developed in order to aid in selecting the optimal pathway. After that, a case study is developed to test the applicability of the model by defining all the economic and technical parameters and solving for the decision variables. Finally, a sensitivity analysis is conducted for the parameters defined in the case study to assess the level of uncertainty they have and their impact on the optimal solution achieved. Each of the previous steps is further elaborated in the following sections of this chapter.

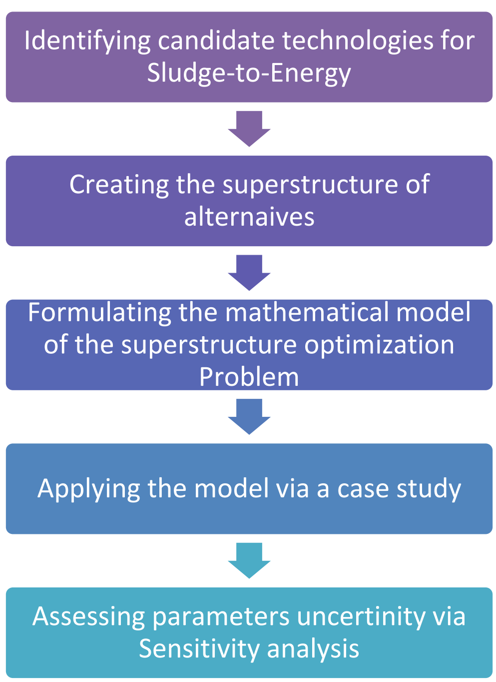


Figure 10 - Decision-making framework for sludge-to-energy process synthesis

4.2 Superstructure Development

The superstructure of alternatives in this work refers to a graphical representation of a network that shows the connections and relationships between the feed stream(s) being processed, potential processing technologies, and intermediate and final products. For the case of the problem being studied, there is a single feed stream crossing the boundary limit of the superstructure which is thickened sewage sludge. The processing units are categorized into biochemical processes, thermochemical processes, and intermediate processes. As shown in the schematic in Figure 11, the biochemical processes covered in this superstructure are MAD, and MAD + THP. The thermochemical processes include Incineration, Gasification, Pyrolysis, SCWO, and SCWG. The intermediate processes comprise mechanical processes like sludge dewatering and thermal processes like sludge thermal drying. Intermediate processes were duplicated to differentiate between those processing digested sludge and those processing undigested sludge. This is because depending on whether a biochemical technology was selected or not, intermediate processes can have varying capacities and are part of different pathways. Three different dewatering technology options are modelled, namely, belt filter dewatering, filter press dewatering, and low-speed centrifuge dewatering.

Each of the biochemical and thermochemical units includes an energy recovery facility that produces energy in the form of electricity or fuels. The final products shown in the superstructure are either value-added products or residual/waste products. Value-added products are those that can be sold in the market, like electricity, Class A biosolids, bio-oil, biochar, and hydrogen. Residual products, like dewatered sludge and ash, are cost-incurring ones that can be disposed into landfills or sent for beneficial use (i.e., use in cement industry for ash, land application for dewatered sludge). For ease of presentation, each material stream was given a distinct colour as explained in the legend of the superstructure diagram. In addition, digested sludge products were differentiated graphically by using dashed lines compared to solid lines for undigested sludge streams. This superstructure illustration lays the foundation for the logical relationships between what will be the building blocks of the mathematical model formulation as demonstrated in the next section.

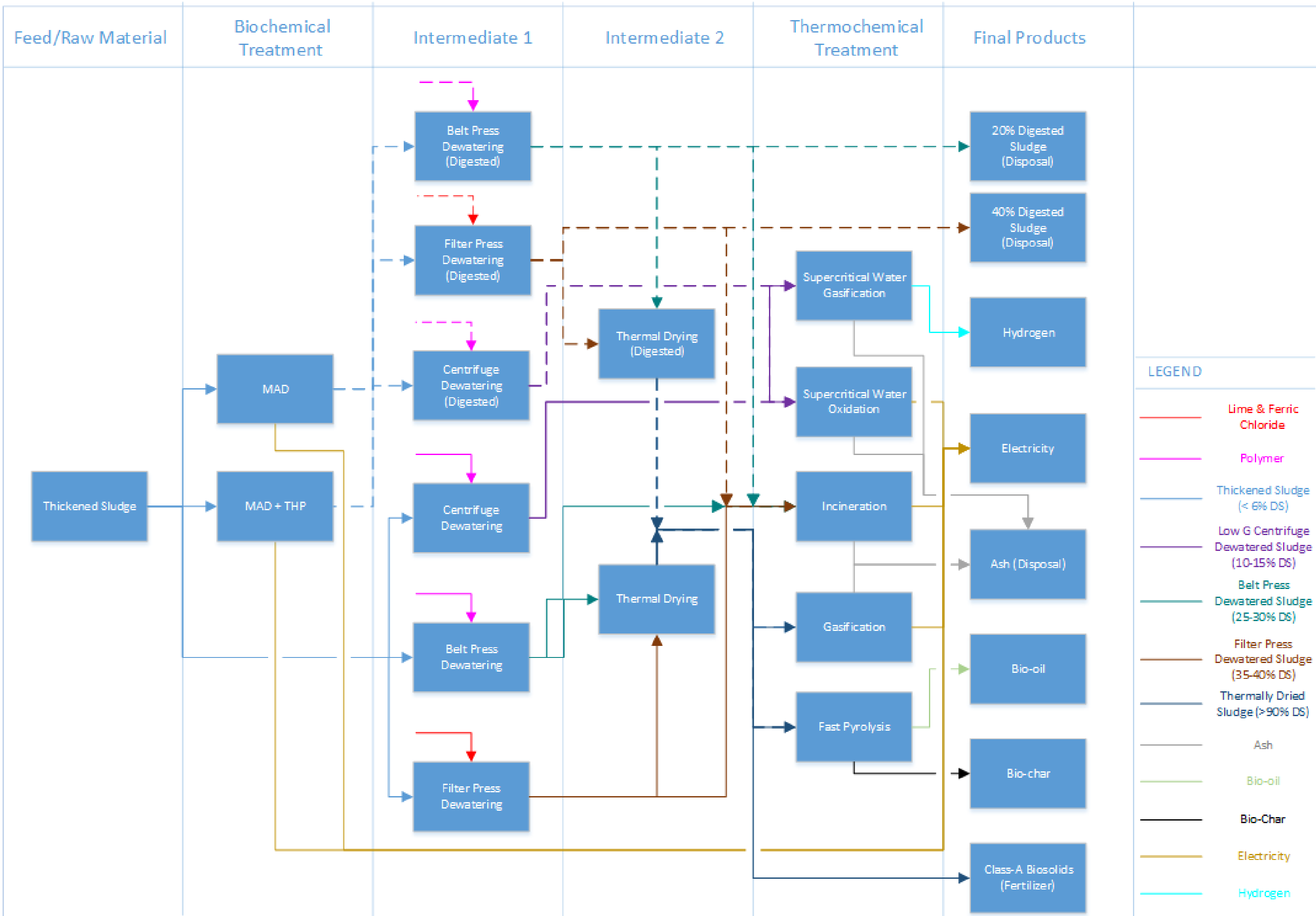


Figure 11 - Superstructure representation of Sludge-to-Energy alternatives

4.3 Mathematical Model Formulation

4.3.1 General

Any optimization problem involves the minimization or maximization of a certain function, called the objective function, which is subject to a set of equality and inequality constraints. Superstructure optimization problems formulations follow the same concept and can be mathematically expressed as follows [69]:

$$
\begin{aligned}
&\min_{x,z} \; C = c^T z + p(x) \\
&\text{s.t.} \quad r(x) = 0 \\
&\qquad\; s(x) + Bz \le 0 \\
&x \in R^n, \quad z \in \{0,1\}^l
\end{aligned}
\tag{1}
$$

where the objective cost function C consists of a) costs related to a discrete decision integer variables vector z which is multiplied by a matrix of relevant cost coefficients c, this matrix usually consists of capital cost parameters, and b) costs related to continuous variables vector x represented in functions $p(x)$ and those are typically costs related to operation and maintenance costs or revenues from products' sales. The objective function is constrained by the physical performance of the process or technology efficiency which is modelled using an equality functions vector $r(x)$ and the logical relations are dictated by inequality functions $s(x)$ that relate to the discrete integer decision variables vector via a coefficients matrix B. Depending on whether functions $p(x)$, $r(x)$, and $s(x)$ are all linear or any of them is non-linear, the problem becomes a Mixed-integer linear program (MILP) or Mixed-integer non-linear program (MINLP) respectively where each type has its applicable algorithms for it to solve.

Equation (1) represents the generalized high-level architecture of such problems, however, in this research, a detailed model following the same general approach but customized to suit the specific needs of our problem will be formulated. Before delving into the modelling convention of individual components of the detailed model, the nomenclature, and relationships between elements of the superstructure are described in this section. The model consists of a group of sets, parameters, variables, and equations. The sets are expressed by a number of bold roman letters (example: **I)**, parameters use light italic roman letters (example: *I*), variables are expressed by italic bold letters (example ***X***). Model elements' identifiers (subscripts and superscripts) can express process blocks (italic letters), streams and their components (normal roman letters). Generic identifiers are light formatted, while if a specific identifier is used, it is **bolded**. The sets can be grouped into two main groups: sets that define the main model elements (i.e., Feed sources, technologies, processes streams, components, and final products), and sets that define the relationships between those elements. The identifiers that are used to describe individual model elements that belong to a corresponding set(s) are listed in Table 3 below:

Table 3 - Model elements identifiers (subscripts and superscripts)

Superstructure Element	**Identifier**	**Description**
General	*i,j,k*	Aliases of subscripts identifiers for feed, process, and product blocks.
	s	Generic identifier of a process stream
	c	Generic identifier of a component in a stream
Feed Source	***TH***	Thickened Sludge
Technologies / Processes	***MAD***	Mesophilic Anaerobic Digestion
	MADT	MAD + Thermal Hydrolysis Pretreatment
	CD	Centrifuge dewatering for digested sludge
	CU	Centrifuge dewatering for undigested sludge
	BPD	Belt press dewatering for digested sludge
	BPU	Belt press dewatering for undigested sludge
	FPD	Filter press dewatering for digested sludge
	FPU	Filter press dewatering for undigested sludge
	TD	Thermal Drying
	INC	Incineration
	GN	Gasification
	PY	Fast Pyrolysis
	SCO	Supercritical Water Oxidation

Superstructure Element	**Identifier**	**Description**
	SCG	Supercritical Water Gasification
Final Products	***DS20***	20% dewatered digested sludge
	DS40	40% dewatered digested sludge
	ASH	Ash
	E	Electricity
	FERT	Class-A Biosolids (Fertilizer)
	BO	Bio-oil from pyrolysis
	BC	Biochar from pyrolysis
	H2	Hydrogen
Process Streams	**THS**	Thickened Sludge
	ADS	Anaerobically Digested Sludge
	E	Electricity
	P	Polymer for chemical conditioning
	L	Lime for chemical conditioning
	FC	Ferric chloride for chemical conditioning
	DWS	Dewatered Sludge
	TDS	Thermally dried sludge
	ASH	Ash
	BO	Bio-oil
	BC	Biochar
	H2	Hydrogen
	VS	Total volatile solids

Superstructure Element	Identifier	Description
Components in process streams	**ASH**	Ash
	DS	Total dry solids (VS + Ash)
	W	Water or moisture in the sludge/biosolids
	E	Electricity
	BO	Bio-oil
	BC	Biochar
	H2	Hydrogen

The sets describing the model elements and their relationships are described in Table 4 below:

Table 4 - Sets of model elements and their relationships

Set	Description
$\mathbf{I}$	Combined set of Feed, process, and final product blocks
$\mathbf{FEED}$	Subset of feed blocks, $\mathbf{FEED} \subset \mathbf{I}$
$\mathbf{PROCESS}$	Subset of processing technologies, $\mathbf{PROCESS} \subset \mathbf{I}$
$\mathbf{PRODUCT}$	Subset of final products, $\mathbf{PRODUCT} \subset \mathbf{I}$
$\mathbf{STR}$	Set of process streams
$\mathbf{CHEM}$	Subset of chemicals streams used for conditioning $\mathbf{CHEM} \subset \mathbf{STR}$
$\mathbf{COMP}$	Set of components of process streams
$\mathbf{S}_i$	Set of descendant block(s) from block $i \in \mathbf{FEED} \cup \mathbf{PROCESS}$. Where $\mathbf{S}_i \subset \mathbf{PROCESS} \cup \mathbf{PRODUCT}$
$\mathbf{P}_i$	Set of precedent block(s) of block $i \in \mathbf{PROCESS} \cup \mathbf{PRODUCT}$. Where $\mathbf{P}_i \subset \mathbf{FEED} \cup \mathbf{PROCESS}$

Set	Description
$\mathbf{STF}_i$	Set of inlet stream(s) applicable with process $i \in$ **PROCESS**. Where $\mathbf{STF}_i \subset \mathbf{STR}$
$\mathbf{STPR}_i$	Set of outlet stream(s) applicable with process $i \in$ **PROCESS**. Where $\mathbf{STPR}_i \subset \mathbf{STR}$
$\mathbf{SCOMP}_s$	Set of component(s) applicable to stream $s \in$ **STR**. Where $\mathbf{SCOMP}_s \subset \mathbf{COMP}$
$\mathbf{FPCO}_i$	Set of component(s) used for specifying the revenue/disposal cost of a final product $i \in$ **PRODUCT**. Where $\mathbf{FPCO}_i \subset \mathbf{COMP}$

Explicit definition of sets describing model elements relationships (i.e. $\mathbf{S}_i, \mathbf{P}_i, \mathbf{STF}_i, \mathbf{STPR}_i, \mathbf{SCOMP}_s$, and $\mathbf{FPCO}_i$) can be found in Appendix A. After specifying the sets defining model elements and their relationships, a group of performance and economic parameters applicable to all the processing technologies are defined and stated in Table 5 below:

Table 5 - Parameters applicable to all processing technologies

Parameter	Description
CAP_i	Maximum processing capacity of a certain process $i \in$ **PROCESS** in tDS/day.
BCC_i	Base (reference) capital cost of process $i \in$ **PROCESS** in $ (USD 2019)
BQ_i	Base (reference) processing capacity of process $i \in$ **PROCESS** used in capital cost calculation.
α_i	Economies of scale exponent of process $i \in$ **PROCESS**.
POC_i	Operating cost parameter for a certain process $i \in$ **PROCESS**.
DPY	Days of operation per year

The next component to be defined for the model formulation is the decision variables. The variables can be grouped in several ways namely: process variables versus economic variables, continuous variables vs integer and/or binary variables, and dependent versus independent variables. In terms of the mathematical model formulation, what matters the most is the distinction between continuous and integer/binary variables because this will play a part in dictating the type of the optimization problem upon solving it. Table 6 below lists the different variables that are part of the general model formulation (processing technology-specific variables will be defined in the subsequent sections).

Table 6 - Variables applicable to general model formulation

Variable	Type	Description
$\boldsymbol{FI}_i^{s,c}$	Process, continuous, dependent	Total inlet flowrate of a component c ∈ **COMP** within a process stream s ∈ **STR** into process i ∈ **PROCESS**.
$\boldsymbol{FO}_i^{s,c}$	Process, continuous, dependent	Total outlet flowrate of a component c ∈ **COMP** within a process stream s ∈ **STR** out of process i ∈ **PROCESS**.
$\boldsymbol{X}_{i,j}^{s,c}$	Process, continuous, dependent	Flowrate of a component c ∈ **COMP** within a process stream s ∈ **STR** going from any block i ∈ **I** to another block j ∈ **I**.
$\boldsymbol{SF}_{i,j}^{s}$	Process, continuous, independent	Split factor of a process stream s ∈ **STR** going from any block i ∈ **I** to another block j ∈ **I**.
$\boldsymbol{z}_i$	Process, binary, independent	Binary variable that dictates whether a certain process i ∈ **PROCESS** exists or not. $\boldsymbol{z}_i \in \{0,1\}$
$\boldsymbol{CC}_i$	Economic, continuous, dependent	Capital cost of a certain process i ∈ **PROCESS** in $ (USD 2019)
$\boldsymbol{OC}_i$	Economic, continuous, dependent	Operating cost of a certain process i ∈ **PROCESS** in $/yr (USD 2019).

The relationship between the different process variables described above can be represented graphically as in Figure 12. For a given process, the flowrate of each applicable component c in an inlet stream s is calculated by summing all the individual flowrates of the same component and stream from the preceding blocks of that process. On the other hand, the individual flowrate of a certain component in a stream going from a certain block to a subsequent one is dictated by a split factor

$\boldsymbol{SF}_{i,j}^{\mathrm{s}}$ ranging from 0 to 1 that is specific to each stream, origin process, and destination block. These concepts are mathematically represented in equations (2) to (7). Equation (8) forces the split factors' total originating from a certain process to equal zero in case the process is not chosen. Similarly, equation (9) forces the total sludge dry solids inlet flowrate to a certain process to be equal to zero in case the process was not chosen. If the process was otherwise selected, this equation ensures the flowrate does not exceed the maximum capacity. Equation (10) forces a minimum flow of 10% of the maximum capacity to enter a certain process if it was selected. The relationship between total inlet flows and outlet flows of relevant components and streams of a certain process is discussed for each block in the next sections.

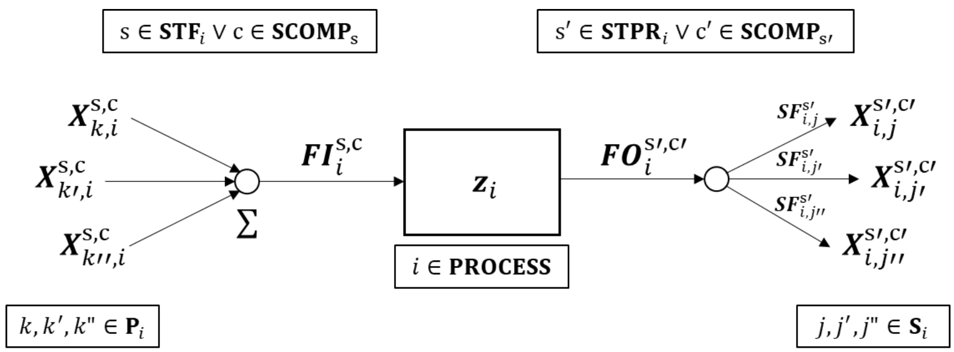


Figure 12 - Graphical representation of relationships between the model's process variables

$$\boldsymbol{FI}_i^{\mathrm{s,c}} = \sum_{\boldsymbol{k}\in\mathbf{P}_i} \boldsymbol{X}_{k,i}^{\mathrm{s,c}},\ \forall\,(i \in \mathbf{PROCESS}\ \wedge\ \mathrm{s} \in \mathbf{STF}_i\ \wedge \mathrm{c} \in \mathbf{SCOMP}_{\mathrm{s}}) \quad (2)$$

$$\boldsymbol{FI}_i^{\mathrm{s,c}} = 0, \forall\,\big(i \in \mathbf{PROCESS}\ \wedge (\mathrm{s} \notin \mathbf{STF}_i\ \vee \mathrm{c} \notin \mathbf{SCOMP}_{\mathrm{s}})\big) \quad (3)$$

$$\boldsymbol{FO}_i^{\mathrm{s,c}} = 0, \forall\,(i \in \mathbf{PROCESS}\ \wedge (\mathrm{s} \notin \mathbf{STPR}_i\ \vee \mathrm{c} \notin \mathbf{SCOMP}_{\mathrm{s}})) \quad (4)$$

$$\boldsymbol{X}_{i,j}^{\mathrm{s,c}} = \boldsymbol{SF}_{i,j}^{s} * \boldsymbol{FO}_i^{\mathrm{s,c}},\ \forall\,(i \in \mathbf{PROCESS}\ \wedge\ j \in \mathbf{S}_i \wedge\ \mathrm{s} \in \mathbf{STPR}_i\ \wedge \mathrm{c} \in \mathbf{SCOMP}_{\mathrm{s}}) \quad (5)$$

$$0 \leq\ \boldsymbol{SF}_{i,j}^{\mathrm{s}} \leq 1,\ ,\ \forall(\,i \in \mathbf{PROCESS}\ \wedge\ j \in \mathbf{S}_i \wedge\ \mathrm{s} \in \mathbf{STPR}_i\,) \quad (6)$$

$$\boldsymbol{SF}_{i,j}^{\mathrm{s}} = 0, \forall\,\big(i \in \mathbf{PROCESS}\ \wedge (\mathrm{s} \notin \mathbf{STF}_j, j \in \mathbf{S}_i)\,\big) \quad (7)$$

$$\sum_{j\in\mathbf{S}_i} \boldsymbol{SF}_{i,j}^{\mathrm{s}} = \boldsymbol{z}_i,\ \forall\,(i \in \mathbf{PROCESS}\ \wedge\ \mathrm{s} \in \mathbf{STPR}_i) \quad (8)$$

$$\boldsymbol{FI}_i^{\mathbf{s,DS}} \leq \boldsymbol{z}_i * CAP_i,\ \forall\,(i \in \mathbf{PROCESS}\ \wedge\ \mathrm{s} \in \mathbf{STF}_i) \quad (9)$$

$$\boldsymbol{FI}_i^{\mathbf{s,DS}} \geq 0.1 *\ \boldsymbol{z}_i * CAP_i,\ \forall\,(i \in \mathbf{PROCESS}\ \wedge\ \mathrm{s} \in \mathbf{STF}_i) \quad (10)$$

It is to be noted that the sets, parameters, variables, and equations stated above are not conclusive of all the mathematical model formulation. More sets, parameters, variables, and equations specific to each block are going to be defined in the next sections.

4.3.2 Thickened Sludge Block

The thickened sludge block represents the feed stream that will be distributed among the different subsequent alternatives. Table 7 below lists all the parameters that are exclusively relevant to this block.

Table 7 - Model elements applicable to Thickened Sludge block

Symbol	Type	Description	Units / Set Elements
$FTHS$	Parameter	Flowrate of thickened sludge to be processed in tonnes of dry solids per day	tDS/day
$FPVS$	Parameter	Feed volatile solids mass percentage of total dry solids flowrate	%
$FPASH$	Parameter	Ash mass percentage of dry solids	%
$PDS_{\boldsymbol{THS}}$	Parameter	Dry solids mass percentage of total sludge flowrate	%

Equations (11) to (13) define the total flowrates of the various components in the thickened sludge stream. Equations (14) to (18) define the individual flowrates of those components going to any of the applicable descendant blocks.

$$\boldsymbol{FO_{TH}^{\mathbf{THS,VS}}} = FPVS * FTHS \tag{11}$$

$$\boldsymbol{FO_{TH}^{\mathbf{THS,ASH}}} = FPASH * FTHS \tag{12}$$

$$\boldsymbol{FO_{TH}^{\mathbf{THS,DS}}} = FTHS \tag{13}$$

$$\boldsymbol{X_{TH,j}^{\mathbf{THS,VS}}} = \boldsymbol{SF_{TH,j}^{THS}} * \boldsymbol{FO_{TH}^{\mathbf{THS,VS}}} , \ \forall \ j \in \mathbf{S}_{\boldsymbol{TH}} \tag{14}$$

$$\boldsymbol{X_{TH,j}^{\mathbf{THS,ASH}}} = \boldsymbol{SF_{TH,j}^{THS}} * \boldsymbol{FO_{TH}^{\mathbf{THS,ASH}}} , \ \forall \ j \in \mathbf{S}_{\boldsymbol{TH}} \tag{15}$$

$$\boldsymbol{X_{TH,j}^{\mathbf{THS,DS}}} = \boldsymbol{X_{TH,j}^{\mathbf{THS,VS}}} + \boldsymbol{X_{TH,j}^{\mathbf{THS,ASH}}}, \ \forall \ j \in \mathbf{S}_{\boldsymbol{TH}} \tag{16}$$

$$\boldsymbol{X}_{\boldsymbol{TH},j}^{\mathbf{THS,W}} = \boldsymbol{X}_{\boldsymbol{TH},j}^{\mathbf{THS,DS}} * \frac{1-PDS_{THS}}{PDS_{THS}}, \ \forall \ j \in \mathbf{S}_{\boldsymbol{TH}} \quad (17)$$

$$\sum_{j \in \mathbf{S}_{\boldsymbol{TH}}} \boldsymbol{SF}_{\boldsymbol{TH},j}^{\mathbf{THS}} = 1 \quad (18)$$

4.3.3 Anaerobic digestion blocks

The anaerobic digestion blocks convert the thickened sludge stream into net electricity to be exported to the grid or used onsite and digested sludge that is sent to any of the dewatering options available. Table 8 below lists all the model elements that are exclusively relevant to this block.

Table 8 - Model elements applicable to Anaerobic Digestion Blocks

Symbol	Type	Description	Units / Set Elements
$\mathbf{AD}$	Set	Subset of anaerobic digestion blocks $\mathbf{DW} \subset \mathbf{PROCESS}$	{*MAD, MADT*}
$VSD_i, i \in \mathbf{AD}$	Parameter	Volatile solids destruction percentage	%
$Y_i^{\boldsymbol{E}}, i \in \mathbf{AD}$	Parameter	Yield of net electricity per tonne dry volatile solids destructed	kWh/tVSD

Equations (19) to (21) define the yield of each component in the outlet product stream of digested sludge, while equation (22) defines the second outlet product stream of electricity generated from biogas utilization.

$$\boldsymbol{FO}_i^{\mathbf{ADS,VS}} = \boldsymbol{FI}_i^{\mathbf{THS,VS}} * (1 - VSD_i), \ \forall \ i \in \mathbf{AD} \quad (19)$$

$$\boldsymbol{FO}_i^{\mathbf{ADS,ASH}} = \boldsymbol{FI}_i^{\mathbf{THS,ASH}}, \ \forall \ i \in \mathbf{AD} \quad (20)$$

$$\boldsymbol{FO}_i^{\mathbf{ADS,DS}} = \boldsymbol{FO}_i^{\mathbf{ADS,VS}} + \boldsymbol{FO}_i^{\mathbf{ADS,ASH}}, \ \forall \ i \in \mathbf{AD} \quad (21)$$

$$\boldsymbol{FO}_i^{\mathbf{E,E}} = \boldsymbol{FI}_i^{\mathbf{THS,VS}} * VSD_i * Y_i^{\boldsymbol{E}}, \ \forall \ i \in \mathbf{AD} \quad (22)$$

Equations (23) and (24) define the capital and operating costs of any of the anaerobic digestion blocks respectively.

$$\boldsymbol{CC}_i = BCC_i * \left(\frac{\boldsymbol{FI}_i^{\mathbf{THS,DS}}}{BQ_i}\right)^{\alpha_i}, \ \forall \ i \in \mathbf{AD} \quad (23)$$

$$\boldsymbol{OC}_i = POC_i * \boldsymbol{FI}_i^{\mathbf{THS,DS}} * DPY, \ \forall \ i \in \mathbf{AD} \quad (24)$$

4.3.4 Dewatering blocks

The dewatering blocks' function is to reduce the moisture content of the influent sludge after being conditioned with a certain chemical that enhances the dewaterability of the sludge. Three dewatering methods are available in the superstructure namely centrifuge, belt press and filter press, each of which is capable of achieving a different degree of cake dryness. For each dewatering method, a distinct block is modelled depending on the type of sludge entering it, undigested thickened sludge, or anaerobically digested sludge. The subsequent processing step/destination differs depending on the dewatering method and its feed. Table 9 below lists all the sets, variables and parameters that are relevant to this block.

Table 9 - Model elements applicable to Dewatering blocks

Symbol	Type	Description	Units / Set Elements
$\mathbf{DW}$	Set	Subset of dewatering processes $\mathbf{DW} \subset \mathbf{PROCESS}$.	$\{CU, CD, BPU, BPD, FPU, FPD\}$
$\mathbf{CH}_i$	Set	Set of matching a certain chemical conditioning stream s ∈ $\mathbf{CHEM}$ to a corresponding dewatering process $i \in \mathbf{DW}$.	{P} for $i = CU, CD, BPU, and\ BPD$ {L, FC} for $i = FPU, and\ FPD$
DR^s	Parameter	Dosage rate of conditioning chemical stream s ∈ $\mathbf{CHEM}$.	tonne/tDS
PDS_i	Parameter	Percentage of total dry solids in dewatering process $i \in \mathbf{DW}$.	%
$\boldsymbol{CH_i^s}$	Variable	Flowrate of conditioning chemical s ∈ $\mathbf{CHEM}$ to a certain dewatering technology $i \in \mathbf{DW}$	tonne/day

In equation (25), the flowrate of the relevant conditioning chemical to a certain dewatering process is defined as a function of the sludge dry solids flowrate multiplied by the dosage rate parameter.

Equations (26) to (29) define the yield of each component in the outlet product stream of the dewatered sludge.

$$\boldsymbol{CH}_i^{\mathrm{s}} = \sum_{s' \in \mathbf{STF}_i} \boldsymbol{FI}_i^{\mathrm{s}',\mathbf{DS}} * DR^{\mathrm{s}},\ \forall\, (i \in \mathbf{DW}\ \wedge\ \mathrm{s} \in \mathbf{CH}_i) \tag{25}$$

$$\boldsymbol{FO}_i^{\mathbf{DWS,VS}} = \sum_{\mathrm{s}' \in \mathbf{STF}_i} \boldsymbol{FI}_i^{\mathrm{s}',\mathbf{VS}},\ \forall\, i \in \mathbf{DW} \tag{26}$$

$$\boldsymbol{FO}_i^{\mathbf{DWS,ASH}} = \sum_{\mathrm{s}' \in \mathbf{STF}_i} \boldsymbol{FI}_i^{\mathrm{s}',\mathbf{ASH}} + \sum_{\mathrm{s} \in \mathbf{CH}_i} \boldsymbol{CH}_i^{\mathrm{s}},\ \forall\, i \in \mathbf{DW} \tag{27}$$

$$\boldsymbol{FO}_i^{\mathbf{DWS,DS}} = \boldsymbol{FO}_i^{\mathbf{DWS,VS}} + \boldsymbol{FO}_i^{\mathbf{DWS,ASH}},\ \forall\, i \in \mathbf{DW} \tag{28}$$

$$\boldsymbol{FO}_i^{\mathbf{DWS,W}} = \boldsymbol{FO}_i^{\mathbf{DWS,DS}} * \frac{1-PDS_i}{PDS_i},\ \forall\, i \in \mathbf{DW} \tag{29}$$

Equations (30) and (31) define the capital and operating costs of the various sludge dewatering blocks respectively.

$$\boldsymbol{CC}_i = BCC_i * \left(\frac{\boldsymbol{FI}_i^{\mathrm{s},\mathbf{DS}}}{BQ_i}\right)^{\alpha_{DW}},\ \forall\, (i \in \mathbf{DW}\ \wedge\ \mathrm{s} \in \mathbf{STF}_i) \tag{30}$$

$$\boldsymbol{OC}_i = POC_{DW} * \boldsymbol{FI}_i^{\mathrm{s},\mathbf{DS}} * DPY,\ \forall\, (i \in \mathbf{DW}\ \wedge\ \mathrm{s} \in \mathbf{STF}_i) \tag{31}$$

4.3.5 Thermal Drying Block

The thermal drying block further reduces the moisture content in the sludge using heat. A single block is modelled to receive sludge from the various dewatering blocks available. The dried sludge is routed to the possible subsequent options namely: pyrolysis and/or selling as Class A biosolids fertilizer. Note: gasification process block contains a thermal dryer within its boundaries (see section 4.3.7). The model elements applicable to the thermal drying block are identified in Table 10 below.

Table 10 - Model elements applicable to the Thermal Drying block

Symbol	Type	Description	Units
$PDS_{\boldsymbol{TD}}$	Parameter	Percentage of total dry solids from thermal drying	%
$\boldsymbol{FWE_{TD}}$	Variable	Total flowrate of water evaporated in the thermal dryer	tonneH2O/day

Equations (32) to (35) define the yield of each component in the outlet product stream of the thermally dried sludge. Equation (36) defines the amount of water/moisture evaporated in the dryer which is a key parameter in sizing the dryer for cost estimating.

$$\boldsymbol{FO_{TD}^{\text{TDS,VS}}} = \boldsymbol{FI_{TD}^{\text{DWS,VS}}} \quad (32)$$

$$\boldsymbol{FO_{TD}^{\text{TDS,ASH}}} = \boldsymbol{FI_{TD}^{\text{DWS,ASH}}} \quad (33)$$

$$\boldsymbol{FO_{TD}^{\text{TDS,DS}}} = \boldsymbol{FI_{TD}^{\text{DWS,DS}}} \quad (34)$$

$$\boldsymbol{FO_{TD}^{\text{TDS,W}}} = \boldsymbol{FO_{TD}^{\text{TDS,DS}}} * \frac{1-PDS_{\boldsymbol{TD}}}{PDS_{\boldsymbol{TD}}} \quad (35)$$

$$\boldsymbol{FWE_{TD}} = \boldsymbol{FI_{TD}^{\text{DWS,W}}} - \boldsymbol{FO_{TD}^{\text{TDS,W}}} \quad (36)$$

Equations (37) and (38) define the capital and operating costs of the thermal drying block respectively.

$$\boldsymbol{CC_{TD}} = BCC_{\boldsymbol{TD}} * \left(\frac{\boldsymbol{FWE_{TD}}}{BQ_{\boldsymbol{TD}}}\right)^{\alpha_{\boldsymbol{TD}}} \quad (37)$$

$$\boldsymbol{OC_{TD}} = POC_{\boldsymbol{TD}} * \boldsymbol{FWE_{TD}} * DPY \quad (38)$$

4.3.6 Incineration Block

The incineration block is modelled to have a single input which is the sludge (either digested or not), and two outputs which are net electricity generated and the residual ash. The net electricity generated is calculated in two steps. First, the heat losses from the incinerator and the heat required for moisture evaporation are both subtracted from the lower heating value of the sludge, this difference resembles the heat recovered in the waste heat boiler and converted to steam. The second step is to multiply the calculated steam enthalpy by the efficiency of the Rankine cycle to get the net electricity produced. Model elements relevant to the incineration block are listed in Table 11.

Note: The LHV of the sludge can be impacted by the addition of lime as a conditioner for the filter press dewatering step. Lime stabilizes/inhibits some of the volatile solids in the sludge; the exact value of the reduction is uncertain and will be subject to sensitivity analysis.

Table 11 - Model elements applicable to the Incineration block

Symbol	Type	Description	Units
$LHV_{\boldsymbol{VS}}$	Parameter	Lower heating value parameter (coefficient) for sludge	MJ/tVDS

λ_W	Parameter	Latent heat of vaporization of water	MJ/tonne
HLF	Parameter	Heat Loss Factor in the incinerator	Dimensionless
η_R	Parameter	Efficiency of Rankine cycle	%
CF_{MJ2kWh}	Parameter	Conversion factor of MJ to kWh	Dimensionless
$\boldsymbol{H_{INC}^{\mathbf{VS}}}$	Variable	Heat flow of volatile solids entering incineration block	kWh(th)/day
$\boldsymbol{H_{INC}^{\mathbf{W}}}$	Variable	Heat required to evaporate moisture in sludge entering incineration block	kWh(th)/day
$\boldsymbol{H_{INC}}$	Variable	Net heat recovered from incineration	kWh(th)/day

Equation (39) specifies the yield of the ash produced out of incineration to be equal to that fed from the incoming dewatered sludge. Equation (40) defines the heat content of the sludge based on its volatile solids content. Equation (41) calculates the amount of heat required to evaporate the moisture content of the sludge. Equation (43) defines the net amount of electricity that can be recovered via a Rankine cycle using the heat input calculated in equation (42) which accounts for the heat losses as well.

$$\boldsymbol{FO_{INC}^{\mathbf{ASH,ASH}}} = \boldsymbol{FI_{INC}^{\mathbf{DWS,ASH}}} \tag{39}$$

$$\boldsymbol{H_{INC}^{\mathbf{VS}}} = LHV_{VS} * \boldsymbol{FI_{INC}^{\mathbf{DWS,VS}}} * CF_{MJ2kWh} \tag{40}$$

$$\boldsymbol{H_{INC}^{\mathbf{W}}} = \lambda_W * \boldsymbol{FI_{INC}^{\mathbf{DWS,W}}} * CF_{MJ2kWh} \tag{41}$$

$$\boldsymbol{H_{INC}} = \left(\boldsymbol{H_{INC}^{VS}} - \boldsymbol{H_{INC}^{W}}\right) * (1 - HLF) \tag{42}$$

$$\boldsymbol{FO_{INC}^{E,E}} = \boldsymbol{H_{INC}} * \eta_R \tag{43}$$

Equations (44) and (45) define the capital and operating costs of the incineration block respectively

$$\boldsymbol{CC_{INC}} = BCC_{\boldsymbol{INC}} * \left(\frac{\boldsymbol{FI_{INC}^{DWS,DS}}}{BQ_{\boldsymbol{INC}}}\right)^{\alpha_{INC}} + 1147\left(\boldsymbol{FO_{INC}^{E,E}}\right)^{0.695} \tag{44}$$

$$\boldsymbol{OC_{INC}} = \left(POC_{\boldsymbol{INC}} * \boldsymbol{FI_{INC}^{DWS,DS}} + POC_{\boldsymbol{ST}} * \boldsymbol{FO_{INC}^{E,E}} \right) * DPY \tag{45}$$

where *ST* refers to a steam turbine unit for electricity generation.

4.3.7 Gasification Block

For modelling the gasification block, the thermal drying unit was included inside its boundaries. The reason behind that is that recycling of heat from syngas combustion is utilized to both dry the sludge and provide the necessary heat for the gasifier (overall endothermic reaction). Modelling the blocks separately with recycle streams will be challenging, so in order to simplify, the units were combined together since there is available data in the literature about net electricity generated from such configuration.

The effect of moisture in the dewatered sludge entering the gasification block on the net electricity produced is negligible at moisture contents below 80% [70]. Therefore, the model will be insensitive on whether the sludge to gasification is from belt press or filter press dewatering units.

The yield of net electricity found in the work of [70] is for certain conditions; i.e. sludge composition, temperature, pressure, sludge drying level. For our modelling purposes, all the conditions are assumed to remain the same for the optimized design, except for the sludge composition (%volatile solids). Accordingly, the net power produced from the work of [70] will be divided by the amount of volatile solids entering in his study and is assumed to increase linearly with %VS. The only additional parameter to be defined that is exclusively applicable to gasification is $YF_{\boldsymbol{GN}}^{\boldsymbol{E}}$ which resembles the yield of net electricity in kWh per tonne dry volatile solids fed to the gasifier.

Equations (46) and (47) define the yields of gasification products as net electricity and ash respectively.

$$\boldsymbol{FO_{GN}^{E,E}} = \boldsymbol{FI_{GN}^{DWS,VS}} * YF_{\boldsymbol{GN}}^{\boldsymbol{E}} \tag{46}$$

$$\boldsymbol{FO_{GN}^{ASH,ASH}} = \boldsymbol{FI_{GN}^{DWS,ASH}} \tag{47}$$

Equations (48) and (49) define the capital and operating costs of the gasification block.

$$\boldsymbol{CC_{GN}} = BCC_{\boldsymbol{GN}} * \left(\frac{\boldsymbol{FI_{GN}^{DWS,DS}}}{BQ_{\boldsymbol{GN}}}\right)^{\alpha_{GN}} \tag{48}$$

$$\boldsymbol{OC}_{GN} = POC_{\boldsymbol{GN}} * \boldsymbol{FI}_{\boldsymbol{GN}}^{\mathbf{DWS,DS}} * DPY \quad (49)$$

4.3.8 Pyrolysis Block

For modelling purposes, linear empirical equations were found in the literature that predicts the yield of both bio-oil and bio-char [22]. The yield parameters are a function of the percentage of volatile solids and total dry solids entering the pyrolysis reactor. The yield of syngas is usually not accounted for in the literature source used since it is of negligible heating value, accordingly, the syngas stream was excluded from our model. The following correction factors $CF_{\boldsymbol{PY}}^{\boldsymbol{BO}}$ and $CF_{\boldsymbol{PY}}^{\boldsymbol{BC}}$ were added to equations 46 and 47 respectively to account for the uncertainty in the coefficients of the empirical equation upon doing the sensitivity analysis for model parameters. Pyrolysis is an endothermic reaction, so the need for an auxiliary fuel exists to reach the required operating conditions. The heat duty required is calculated as the summation of the heat of drying any residual moisture, the sensible heat to reach reaction temperature, and the heat of reaction. From the heat duty calculated, the amount of natural gas required is calculated to satisfy the energy balance and should be used in estimating the operating cost parameters for the unit.

Equations (50) and (51) define the yields of fast pyrolysis products, bio-oil and biochar, in their respective order.

$$\boldsymbol{FO}_{\boldsymbol{PY}}^{\mathbf{BO,BO}} = \left(63.68\% * \boldsymbol{FI}_{\boldsymbol{PY}}^{\mathbf{TDS,VS}} - 11.34\% * \boldsymbol{FI}_{\boldsymbol{PY}}^{\mathbf{TDS,DS}}\right) * CF_{\boldsymbol{PY}}^{\boldsymbol{BO}} \quad (50)$$

$$\boldsymbol{FO}_{\boldsymbol{PY}}^{\mathbf{BC,BC}} = -78.95\% * \boldsymbol{FI}_{\boldsymbol{PY}}^{\mathbf{TDS,VS}} + 98.79\% * \boldsymbol{FI}_{\boldsymbol{PY}}^{\mathbf{TDS,DS}} * CF_{\boldsymbol{PY}}^{\boldsymbol{BC}} \quad (51)$$

Equations (52) and (53) define the capital and operating costs of the pyrolysis block respectively.

$$\boldsymbol{CC}_{\boldsymbol{PY}} = BCC_{\boldsymbol{PY}} * \left(\frac{\boldsymbol{FI}_{\boldsymbol{PY}}^{\mathbf{DWS,DS}}}{BQ_{\boldsymbol{PY}}}\right)^{\alpha_{PY}} \quad (52)$$

$$\boldsymbol{OC}_{\boldsymbol{PY}} = POC_{\boldsymbol{PY}} * \boldsymbol{FI}_{\boldsymbol{PY}}^{\mathbf{DWS,DS}} * DPY \quad (53)$$

4.3.9 SCWO and SCWG blocks

The SCWO and SCWG blocks are modelled in a way to simply convert the volatile solids portion of the sludge fed into the block to the respective energy product of each unit. Table 12 lists the yield parameters defined for each of these two processes in the model.

Table 12 – Model parameters applicable to SCWO and SCWG blocks

Symbol	Type	Description	Units
YF_{SCO}^{E}	Parameter	Yield of net electricity per tonne dry volatile solids fed to the SCWO block	kWh/tVS
YF_{SCG}^{H2}	Parameter	Yield of hydrogen per tonne dry volatile solids fed to the SCWG block	kgH2/tVS

Equation (54) defines the electricity product yield from SCWO while equation (56) defines that of hydrogen from SCWG. Equations (55) and (57) calculate the ash product yield from SCWO and SCWG respectively.

$$\boldsymbol{FO_{SCO}^{\mathrm{E,E}}} = \boldsymbol{FI_{SCO}^{\mathrm{DWS,VS}}} * Y_{SCO}^{E} \tag{54}$$

$$\boldsymbol{FO_{SCO}^{\mathrm{ASH,ASH}}} = \boldsymbol{FI_{SCO}^{\mathrm{DWS,ASH}}} \tag{55}$$

$$\boldsymbol{FO_{SCG}^{\mathrm{H2,H2}}} = \boldsymbol{FI_{SCG}^{\mathrm{DWS,VS}}} * Y_{SCG}^{H2} \tag{56}$$

$$\boldsymbol{FO_{SCG}^{\mathrm{ASH,ASH}}} = \boldsymbol{FI_{SCG}^{\mathrm{DWS,ASH}}} \tag{57}$$

The economic variables of capital and operating costs of SCWO and SCWG are defined in equations (58) to (59).

$$\boldsymbol{CC_{SCO}} = BCC_{SCO} * \left(\frac{\boldsymbol{FI_{SCO}^{\mathrm{DWS,DS}}}}{BQ_{SCO}}\right)^{\alpha_{SCO}} \tag{58}$$

$$\boldsymbol{OC_{SCO}} = POC_{SCO} * \boldsymbol{FI_{SCO}^{\mathrm{DWS,VS}}} * DPY \tag{59}$$

$$\boldsymbol{CC_{SCG}} = BCC_{SCG} * \left(\frac{\boldsymbol{FI_{SCG}^{\mathrm{DWS,DS}}}}{BQ_{SCG}}\right)^{\alpha_{SCG}} \tag{60}$$

$$\boldsymbol{OC_{SCG}} = POC_{SCG} * \boldsymbol{FI_{SCG}^{\mathrm{DWS,DS}}} * DPY \tag{61}$$

4.3.10 Objective function

The objective function to be minimized in the optimization problem formulation is the net annual cost defined in equation (62) as the difference between annual costs and annual revenues. The annual costs comprise of the total annualized capital costs (defined by equations (63) and (64)), total annual operating costs of the optimal pathway technologies chosen by the model, as in equation (65), and the total disposal costs of the byproducts produced (equation (66)). The total annual revenue from sales of final products is specified in equation (67). The total flow of each final product or byproduct is defined in equation (68) and used in the calculation of revenue and disposal costs variables. The model elements specific to defining the equations related to the objective function are listed in Table 13below:

Table 13 - Model elements applicable to the objective function definition

Symbol	Type	Description	Units / Set Elements
REVP	Set	Subset of revenue-generating products **REVP** $\subset$ **PRODUCT**	*{E, Fert, BO, BC, H2}*
DISP	Set	Subset of cost-incurring products to be disposed **DISP** $\subset$ **PRODUCT**	*{DS20, DS40, ASH}*
$\boldsymbol{NETCOST}$	Variable	Objective function variable to be minimized representing the net production cost of the chosen pathway	\$/yr (USD 2019).
$\boldsymbol{TACC}$	Variable	Total annualized capital costs of the chosen processes in the optimal pathway.	\$/yr (USD 2019).
$\boldsymbol{TOC}$	Variable	Total annualized operating costs of the chosen processes in the optimal pathway.	\$/yr (USD 2019).
$\boldsymbol{TADC}$	Variable	Total annual disposal costs from the disposal of final byproducts.	\$/yr (USD 2019).

$\boldsymbol{TREV}$	Variable	Total revenues from selling of final products.	\$/yr (USD 2019).
$\boldsymbol{FPI}_i$	Variable	Total flowrate of a final product $i \in$ **PRODUCT**	unit product / day
AF	Parameter	Annualized capital charge ratio	dimensionless
d	Parameter	Interest/discount rate	%
n	Parameter	Number of years of the project life	yr
SP_i	Parameter	Price of selling of a final product $i \in$ **REVP**.	\$/unit product
DC_i	Parameter	Disposal cost of a final product $i \in$ **DISP**.	\$/unit product

$$\boldsymbol{NETCOST} = \boldsymbol{TACC} + \boldsymbol{TOC} + \boldsymbol{TADC} - \boldsymbol{TREV} \quad (62)$$

$$\boldsymbol{TACC} = AF * \sum_{i \in \mathbf{PROCESS}} \boldsymbol{z}_i * \boldsymbol{CC}_i \quad (63)$$

$$AF = \frac{d*(1+d)^n}{(1+d)^n - 1} \quad (64)$$

$$\boldsymbol{TOC} = \sum_{i \in \mathbf{PROCESS}} \boldsymbol{z}_i * \boldsymbol{OC}_i \quad (65)$$

$$\boldsymbol{TADC} = \sum_{i \in \mathbf{DISP}} \boldsymbol{FPI}_i * DC_i * DPY \quad (66)$$

$$\boldsymbol{TREV} = \sum_{i \in \mathbf{REVP}} \boldsymbol{FPI}_i * SP_i * DPY \quad (67)$$

$$\boldsymbol{FPI}_i = \sum_{\mathrm{s} \in \mathbf{STF}_i} \sum_{\mathrm{c} \in \mathbf{FPCO}_i} \sum_{k \in \mathbf{P}_i} \boldsymbol{X}_{k,i}^{\mathrm{s,c}}, \ \forall\, i \in \mathbf{PRODUCT} \quad (68)$$

4.4 Case Study

4.4.1 Case Study Parameters

The parameters in the mathematical model formulation discussed in Section 4.3 were given approximate values for the purpose of performing a case study for a hypothetical sludge treatment plant. The values of the parameters were either assumed or estimated from various sources to help illustrate the use of the optimization model. Table 14 is listing the feed properties-related parameters, while Table 15 lists the capital and operating costs for each technology, Table 16 lists the selling prices and disposal costs of the final products, and finally, Table 17 lists the process performance-related parameters. The capital and operating costs were gathered from different sources in the literature that varied in currency and year of study; the costs were adjusted for inflation using the Chemical Engineering Plant Cost Index (CEPCI) [71] for the year 2019 and were then converted to US dollars (USD / $) for consistency. The economies of scale exponent α_i was assumed to be 0.6 for all the technologies. The case study is evaluated for a project lifetime (n) of 20 years at an interest/discount rate (d) of 7.5% [72]. Continuous chemical processing plants typically operate 8,000 hours per year, hence, the DPY parameter is assumed to be 333 days/year.

Table 14 – Feed Properties Parameters

Parameter	**Value**	**Units**
$FTHS$	100	tDS/day
$FPVS$	70	%
$FPASH$	30	%
$PDS_{\boldsymbol{THS}}$	5	%

Table 15 - Capital and Operating Costs of Technologies

Technology	BCC_i (MM$)	BQ_i (tDS/day)	POC_i ($/tDS)	Ref.
MAD	31.86	100	52	[73]
MADT	33.26	100	62	[73]
CD	2.16	50	58	[51]
CU	2.16	50	58	[51]
BPD	6.6	50	69	[51]

Technology	BCC_i (MM$)	BQ_i (tDS/day)	POC_i ($/tDS)	Ref.
BPU	6.6	50	69	[51]
FPD	8.2	50	134	[51]
FPU	8.2	50	134	[51]
TD	12.59	480*	26**	[74]
INC	34.62	130	95	[75], [76]
GN	2.09	5	154	[38]
PY	8.26	50	100	[76]
SCO	9	14	113***	Correspondence with SCFI [46]
SCG	18.44	24	175	[48]

* tH2O(evaporated)/day

**$/ tH2O(evaporated)

***$/ tVS

Table 16 - Final Products Disposal Costs and Selling Prices

Final Product	DC_i ($/tonne)	SP_i ($/tonne)	Ref.
DS20	250	N/A	[75]
DS40	125	N/A	[75]
ASH	77	N/A	[75]
E	N/A	0.08	[77]
FERT	N/A	30	[78]
BO	N/A	285*	[79]
BC	N/A	200	[80]
H2	N/A	2**	[81]

*Assuming a price equivalent to 70% of crude oil of price ≈ 60 $/bbl.

**$/kg

Table 17 - Technologies Performance-Related Parameters

Parameter	Value	Units	Ref.
$VSD_{\boldsymbol{MAD}}$	50	%	[73]
$Y_{\boldsymbol{MAD}}^{\boldsymbol{E}}$	2,390	kWh/tVSD	[73]

Parameter	Value	Units	Ref.
$VSD_{\boldsymbol{MADT}}$	60	%	[73]
$Y_{\boldsymbol{MADT}}^{\boldsymbol{E}}$	2,390	kWh/tVSD	[73]
$DR^{\boldsymbol{P}}$	0.004	tonne/tDS	[50]
$DR^{\boldsymbol{L}}$	0.1	tonne/tDS	[50]
$DR^{\boldsymbol{FC}}$	0.07	tonne/tDS	[50]
$PDS_{\boldsymbol{CU}}, PDS_{\boldsymbol{CD}}$	10	%	[51]
$PDS_{\boldsymbol{BPU}}, PDS_{\boldsymbol{BPD}}$	20	%	[51]
$PDS_{\boldsymbol{FPU}}, PDS_{\boldsymbol{FPD}}$	40	%	[51]
$PDS_{\boldsymbol{TD}}$	90	%	Typical
$LHV_{\boldsymbol{VS}}$	21,000	MJ/tVDS	[82]
$\lambda_{\boldsymbol{W}}$	2,260	MJ/tonne	Steam Table
HLF	0.05	Dimensionless	assumed
η_R	25	%	[76]
CF_{MJ2kWh}	0.27778	Dimensionless	
$YF_{\boldsymbol{GN}}^{\boldsymbol{E}}$	1,368	kWh/tVS	[38]
CF_{PY}^{BO}	1	Dimensionless	
$CF_{\boldsymbol{PY}}^{\boldsymbol{BC}}$	1	Dimensionless	
$YF_{\boldsymbol{SCO}}^{\boldsymbol{E}}$	825	kWh/tVS	Correspondence with SCFI [46]
$YF_{\boldsymbol{SCG}}^{\boldsymbol{H2}}$	112	kgH2/tVS	[48]

4.5 Sensitivity Analysis

The model economic parameters used in the case study are subject to several sources of uncertainty rooting from the inconsistent basis for factors used in capital cost calculations in the various sources, the assumption that operating costs vary linearly with the processing capacity, volatility of products selling prices and the market demand, uncertainty in possible government incentives for each technology. The model technical performance-related parameters are also prone to a level of uncertainty due to the infancy of some of the technologies so learning effects and developments can apply, different sludge characteristics that the original sources relied on, scalability issues, etc. Consequently, the need to assess the model results' sensitivity to each of the relevant parameters is a necessity. The capital and operating costs of each technology are usually estimated from preliminary techno-economic studies for feasibility purposes. This type of studies corresponds to a Class 4 cost estimate as defined by the Association for the Advancement of Cost Engineering (AACE) and can have an accuracy of up to +50% to -30% [83]. This range is used for the sensitivity analysis runs for capital and operating costs parameters. Selling prices are assessed for the following ranges: Electricity price from 6 to 30 cents per kWh, fertilizer price from 20 to 100 $/tonne, bio-oil from 100 to 500 $/tonne (15 to 70 $/bbl of bio-oil), biochar from 100 to 500 $/tonne, and H_2 from 1 to 5 $/kg. Disposal costs of dewatered sludge and ash are varied from 25 to 75 $/wet tonne of solids and from 40 to 100 $/tonne of ash respectively. The discount rate is also being varied between 5% to 10%. As far as performance-related parameters are concerned, yield parameters and sludge LHV are varied by ±30%. The percentage of dry solids produced from belt press and filter press dewatering is varied between 12%-37% and 27%-46% respectively; These ranges cover the whole spectrum of dewatering efficiencies, as per the data in Figure 9, for those two technologies to account for extreme cases of sludge composition variations. Finally, the feed characteristics are examined as follows: inlet flowrates from 50 tDS/day to 150 tDS/day and composition of sludge VS% from 50% to 80% with a corresponding Ash% of 50% to 20%. The results of the sensitivity analysis runs where the objective function value (i.e., net cost) has changed will be reported as well as whether the change in objective function value is accompanied by a change in the optimal processing pathway.

Chapter 5
Results and Discussion

5.1 Base Case Results

The optimization model formulation proposed in section 4.3 together with the case study parameters values in section 4.4 were entered into GAMS software version 24.5.6 to solve it for results. The GAMS code for the model and case study can be found in Appendix B. The BARON solver [84] version 15.9.22 was used to solve the MINLP model guaranteeing global optimality within a reasonable runtime. The software was run on a computer with an Intel® Xeon® CPU E5-2620 v3 dual processors at 2.40 GHz each, with an installed RAM of 32 GB, and Windows Server® 2012 R2 64-bit operating system. The model and solver statistics are summarized in Table 18 below:

Table 18 - Model and Solver Statistics

Model Statistics		**Solver Statistics**	
Single Equations	635	Solver	BARON
Single Variables	418	Optimality Tolerance	10^{-6}
Non-linear matrix entries	371	Branch-and-reduce iterations	41
Discrete Variables	14	Max. no. of nodes in memory	21
Non-zero elements	1,700	CPU Time (s)	70.72

The optimal processing pathway is determined by looking at the results of both the discrete variable $\boldsymbol{z_i}$ and the contentious variable $\boldsymbol{SF^{s}_{i,j}}$; where the first states the choice of a certain technology and the latter foresees whether a certain technology product stream is split between more than one destination. The non-zero z variables obtained in the solution were for processes identifiers ***FPU***, ***TD***, ***PY*** with the final products being bio-oil and biochar as per the split factors results. Figure 13 shows a schematic for the optimal processing route with streams flowrates.

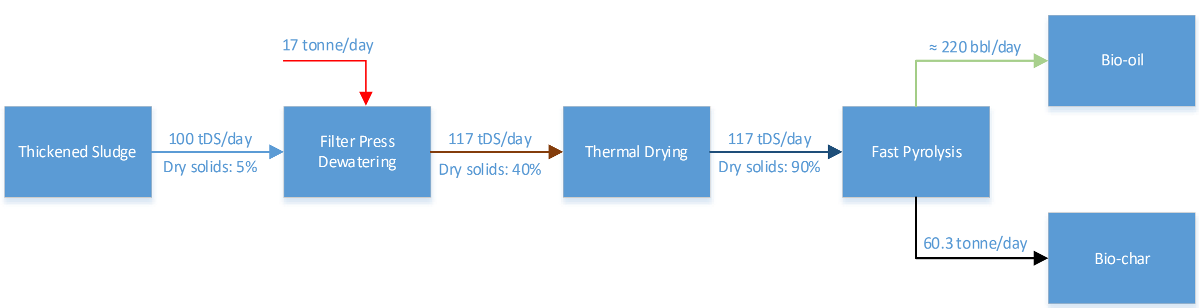
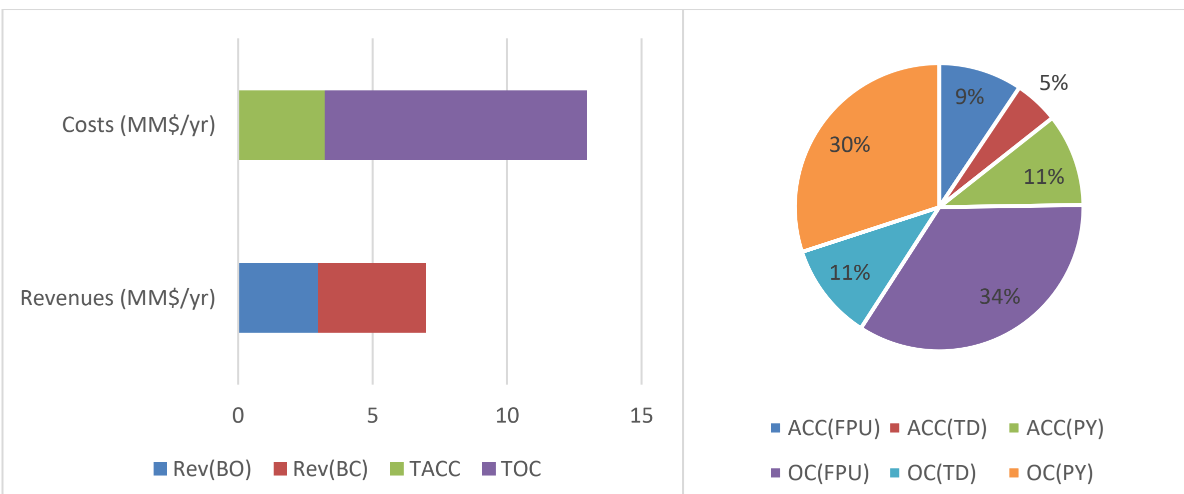


Figure 13 - Optimal Solution Pathway with products flowrates

The annual net cost for this pathway is approximately 6 million $/year for a daily load of 100 tDS of sludge while the specific cost of sludge treatment comes to 180 $/tDS processed. This cost of treatment per tonne of dry sludge is in the same order of magnitude with reported ranges between 100-800 $/tDS of various conventional sludge handling methods (i.e. landfilling, land application, and incineration) [85] . This implies that the parameters used for the case study are practical enough for demonstrating the applicability of the proposed optimization model. The annual costs are close to 13 million $/year where 75% of that cost is attributed to operating costs of the different technologies and the remaining 25% are for the annualized capital cost payments. The annual revenues are 7 million $/year with bio-oil sales contributing to 43% of the total revenue and biochar 57%. Figure 14(a) shows the revenues from products sales of the selected pathway in comparison to the total costs. Figure 14(b) illustrates the breakdown of costs between the different technologies in the selected pathway. It is worth mentioning that the operating cost of the filter press dewatering process accounts for the highest portion of the total costs with 34% followed by pyrolysis operating cost with 30%. The capital cost of the dewatering step is also comparable to that of the pyrolysis. This shows how significant and important the dewatering step is to the whole processing route.



(a) (b)

Figure 14 – (a) Optimal Pathway Costs and Revenues (b) Optimal Pathway Costs Breakdown

5.2 Sensitivity Analysis Results

5.2.1 Feed Characteristics

5.2.1.1 Feed Flowrate

The changes of feed flowrate in the studied ranges, from 50 to 150 tDS/day, did not impact the optimal processing route that was selected in the base case scenario results. Nevertheless, there were obviously changes in the objective function or the net cost value (these two terms are used interchangeably in this chapter) as presented in Figure 15. To see the effect of economies of scale, the percentage of net cost increase per a 10 tDS/day increase in feed flowrate was added in the same plot. As expected, the percentage of additional net annual costs required decreases with increasing the capacity from 15% per each extra 10 tDS/day at 60 tDS/day capacity to 5.7% at 150 tDS/day.

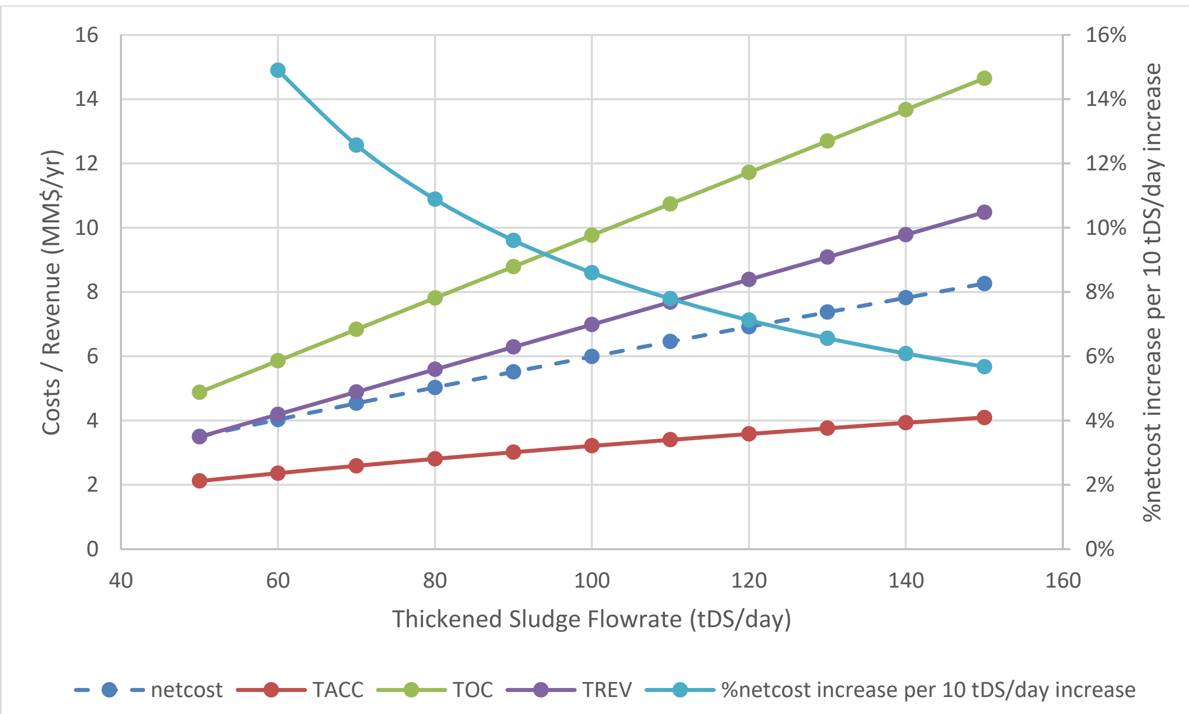


Figure 15 - Sensitivity Analysis of Economic Variables (MM$/yr) with Feed Flowrate

However, it is not yet clear from the above results which of the net costs components (i.e., $\boldsymbol{TACC}$, $\boldsymbol{TOC}$, and $\boldsymbol{TREV}$) has the most underlying impact on the net cost reduction. Therefore, another method to examine the capacity effects is presented which is to conduct the comparison against the various economic variables but per unit tonne of dry sludge treated. The specific costs/revenue variables are suffixed by the asterisk symbol (*) and plotted against different feed flowrate values as shown in Figure 16. It is observed that the specific operating costs and revenues in $/tDS are constant across the whole spectrum of capacities studied at values of 293 $/tDS and 210 $/tDS respectively. Thus, these two components are not playing a significant role in the economies of scale. On the other hand, the annualized capital costs per unit of sludge are exponentially reducing with increasing capacities and hence are the sole driver behind the changes in the specific net cost results. The rate of change in specific annual capital costs, and accordingly that of specific net costs, decelerates with increasing capacity from a 4% reduction per each extra 10 tDS/day of feed flowrate at an initial capacity of 60 tDS/day to 1.5% at 150 tDS/day. This indicates that the effects of scaling economies are minimal at capacities higher than 150-200 tDS/day and that the specific net costs will asymptote at values close to 155-160 $/tDS.

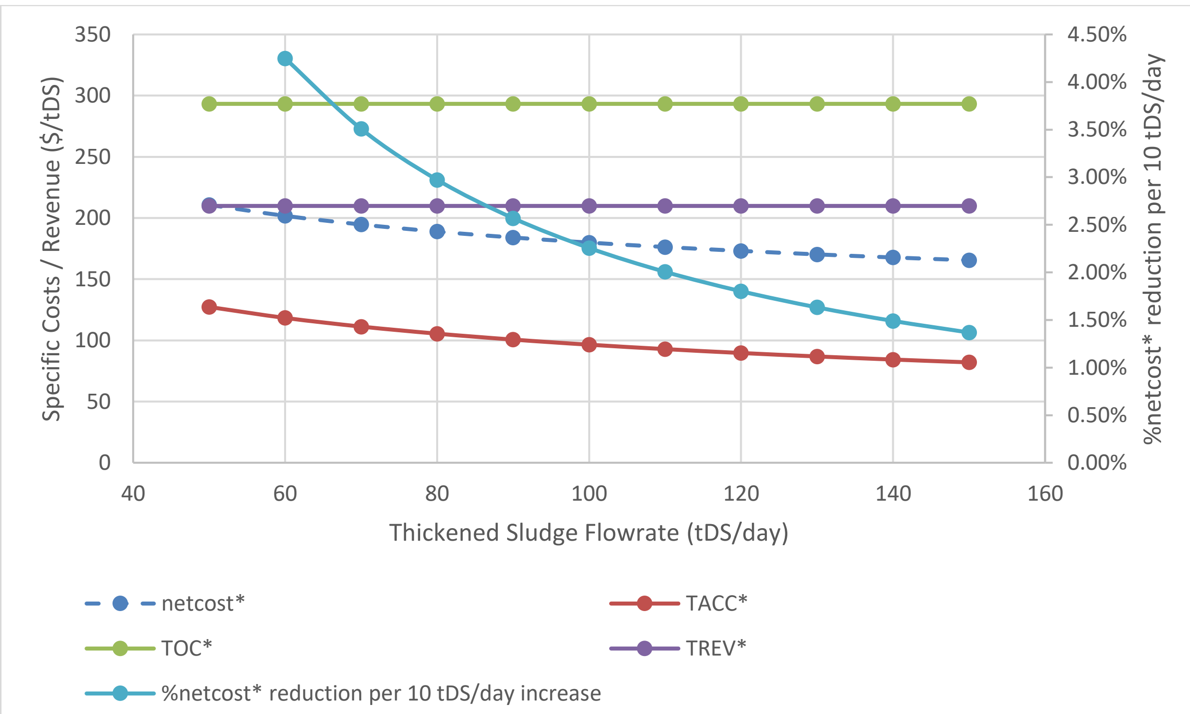


Figure 16 - Sensitivity Analysis of Specific Economic Variables ($/tDS) with Feed Flowrate

5.2.1.2 Feed Composition

The impact of changing the composition of the sewage sludge on the objective function is seen to be minimal. As shown in Figure 17, a 5% increase in the sludge volatile solids percentage, leads only to a reduction of approximately 0.65% in the net cost primarily due to the revenue increases from higher bio-oil yields at the expense of biochar. Thus, the maximum variation expected in the net cost for a composition change of 30% (i.e., from 50% VS to 80%) is close to 3.8% which is not trivial if compounded annually, however, it does not undermine the feasibility of the processing route if a certain wastewater treatment facility is generating sludges with lower organic contents. The optimal processing pathway did not change with varying the composition and this is visible also in the figure from the constant capital and operating costs that are depending mainly on the total amount of dry solids regardless of their components analysis for the chosen processing route.

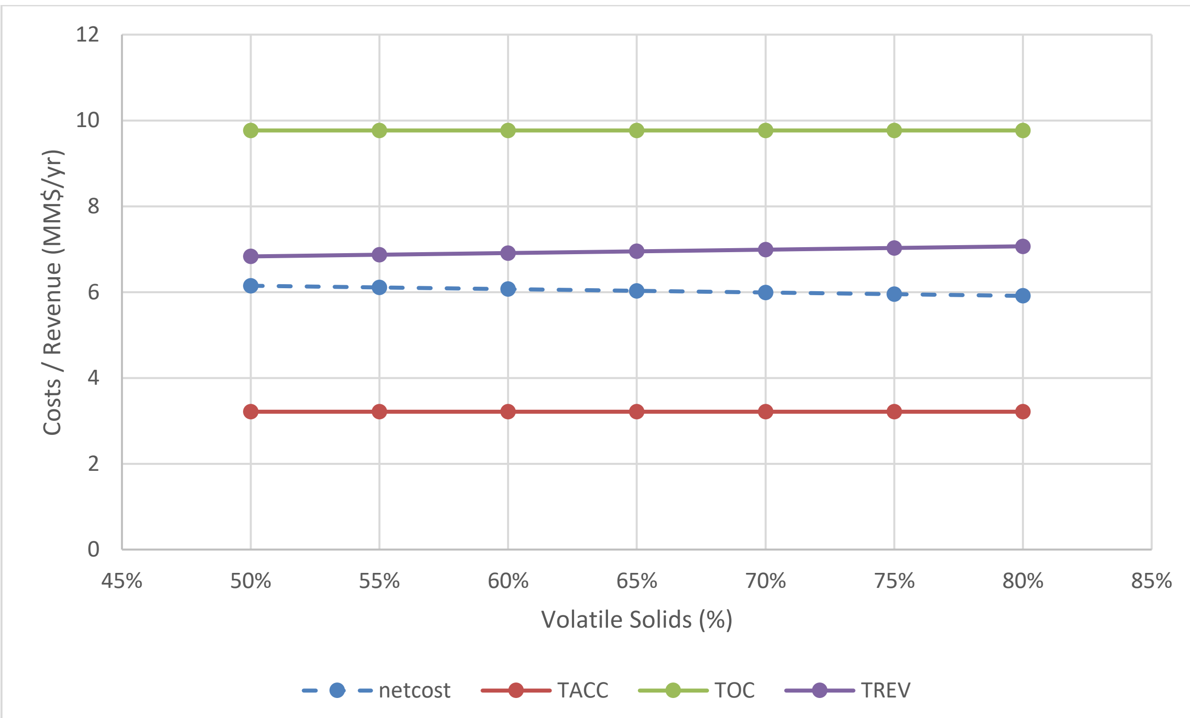


Figure 17 - Sensitivity Analysis of Economic Variables (MM$/yr) with Feed Composition

5.2.2 Economic Parameters

5.2.2.1 Capital and Operating Costs

The objective function value is sensitive to any capital and/or operating cost variations of all the technologies present in the optimal pathway of the base case, namely: ***FPU***, ***TD***, and ***PY***. The percentage of change in capital cost and operating cost parameters of those technologies are plotted against % change in the objective function (compared to base case results) and demonstrated in Figure 18 and Figure 19 respectively. The objective function value plateaus after an increase greater than 20%

for pyrolysis operating cost, this is because at such value the optimization model decides to discard pyrolysis technology from the optimal pathway and the thermally dried biosolids are chosen to be sold as fertilizers instead of being further processed. Similarly, with an increase in ***FPU*** operating costs higher than 10%, the net cost stagnates and the optimal pathway changes to ***BPU***, ***TD***, ***PY***. Reductions in ***FPU*** operating costs have the most significant impacts on net cost where at -30% the corresponding decrease in objective function value is 22%.

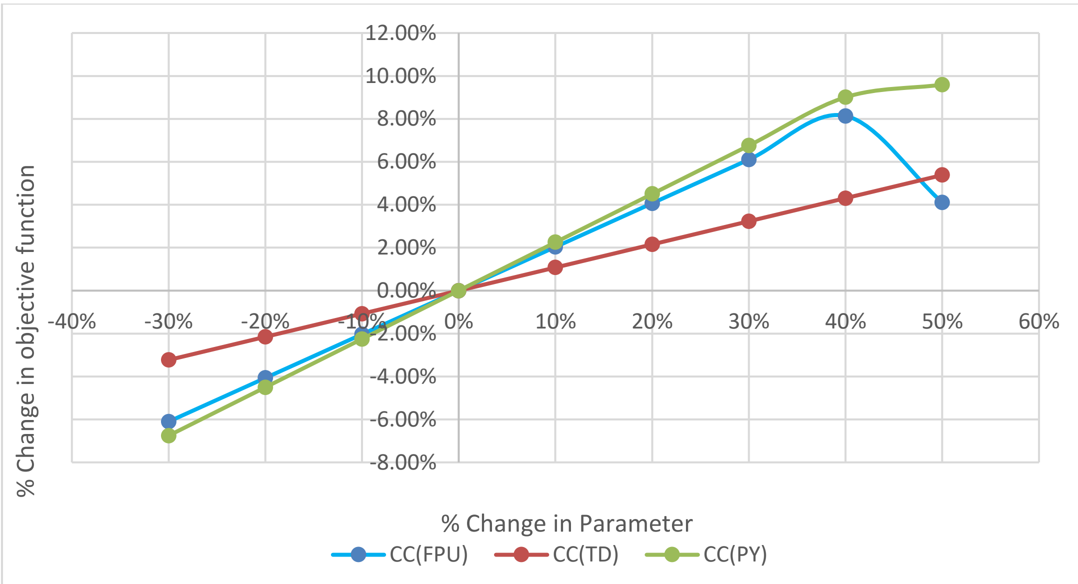


Figure 18 - Sensitivity Analysis of Optimal Pathway Technologies' Capital Cost Parameters

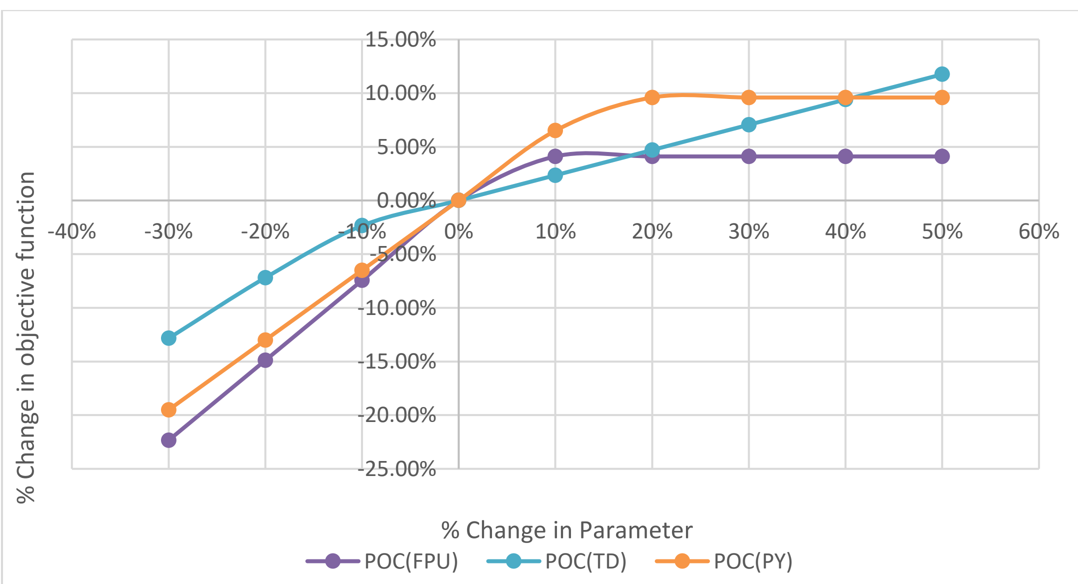


Figure 19 - Sensitivity Analysis of Optimal Pathway Technologies' Operating Cost Parameters

MADT was the only technology outside the base case optimal pathway that the capital cost parameter of which had an impact on the net cost (objective function). This impact appears only at a 30% reduction of ***MADT*** capital cost which led to a 4% decrease in the net cost and a different optimal pathway as shown in Figure 20 where the thickened sludge undergoes thermal hydrolysis pre-treatment and anaerobic digestion before being eventually sent to the pyrolysis pathway of the base case. This adds an additional energy product in the form of electricity recovered from MAD biogas.

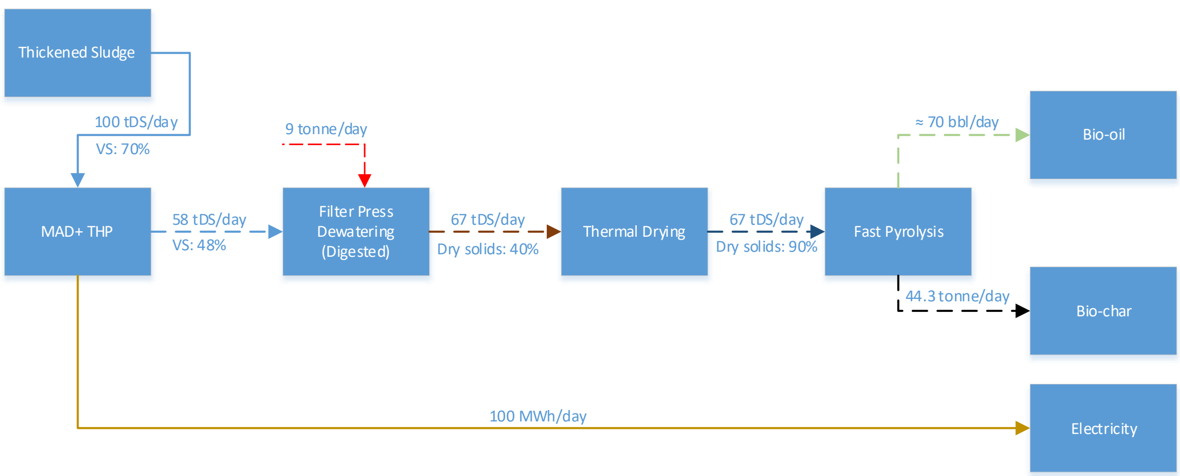


Figure 20 - Optimal Pathway at 30% Reduction of MADT Capital Cost

As far as the remaining technologies' operating cost parameters are concerned, at -30% for ***FPD***, a slight reduction in the net cost of approximately 1% can be attributed to a corresponding optimal processing pathway similar to that was presented in Figure 20. Furthermore, reductions in operating costs of ***BPU*** by 20% and 30% correspond to the objective function value dropping by 7% and 3.5% respectively. The resulting optimal pathway is like that of the base case except that ***FPU*** gets replaced by ***BPU*** which produces a sludge of 20% solids in comparison to the 40% solids produced by ***FPU***. The remaining operating cost parameters for the other technologies were found to be insensitive to both the objective function as well as the optimal pathway choice.

5.2.2.2 Products Selling and Disposal Prices

All the final products' selling prices had an impact on the objective function value when compared to the base case. Electricity prices appear to be the most sensitive parameter when compared to the remaining final products' selling prices. The highest price studied for electricity (30 cents/kWh) can bring the net cost down by -130% compared to the base case results, which leads to having a net profit at such a rate. The optimal pathway chosen at this electricity price is ***MADT***, ***BPD***, ***GN***. Such price is much higher than the average prices for industrial use, thus accounting for more optimistic scenarios of government incentives to electricity from waste such as feed-in-tariff (FIT) and/or tax credits policies. Followed by electricity, the selling prices of biochar and hydrogen were the second most sensitive to changes. At their higher limits (500 \$/tonne of biochar and 5 \$/kg H_2), they cause a reduction close to 100% of the objective function value compared to the base case scenario. The optimal pathway for biochar's highest price stays the same as the base case, while for H_2 it changes to ***CU+SCG*** even at prices as low as 3 \$/kgH_2. This shows the promising potential of that technology, especially with the future higher demands of a sustainable hydrogen economy. The objective function value was least sensitive to the prices of bio-oil and Class A biosolids fertilizer relative to the remaining products. However, significant reductions of approximately 40% to the net costs are achievable at the higher end of the price range studied.

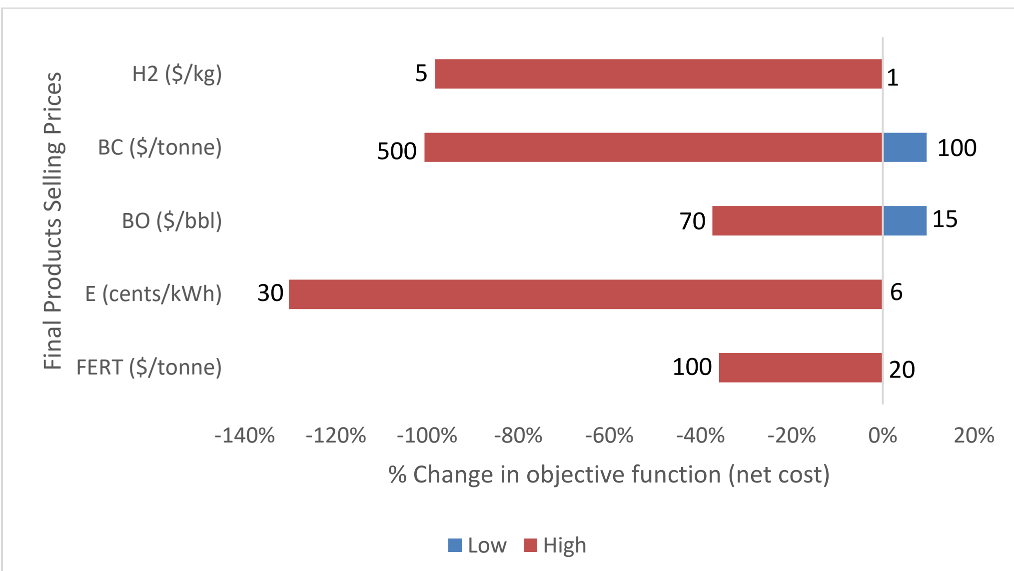


Figure 21 - Sensitivity Analysis of Final Products Selling Prices

Changes in the disposal costs of the by-products (i.e. dewatered sludge, ash) did not impact neither the optimal pathway selected by the model nor the objective function value.

5.2.2.3 Discount Rate

The objective function value is sensitive to variations of the discount rate d, however, the optimal pathway stays the same. As shown in Figure 22, an incremental change of ±0.5% in d, leads to a ±2% change in the objective function which is a significant change. This suggests that at higher rates of inflation trends, the investment in such projects can be less attractive without further incentives.

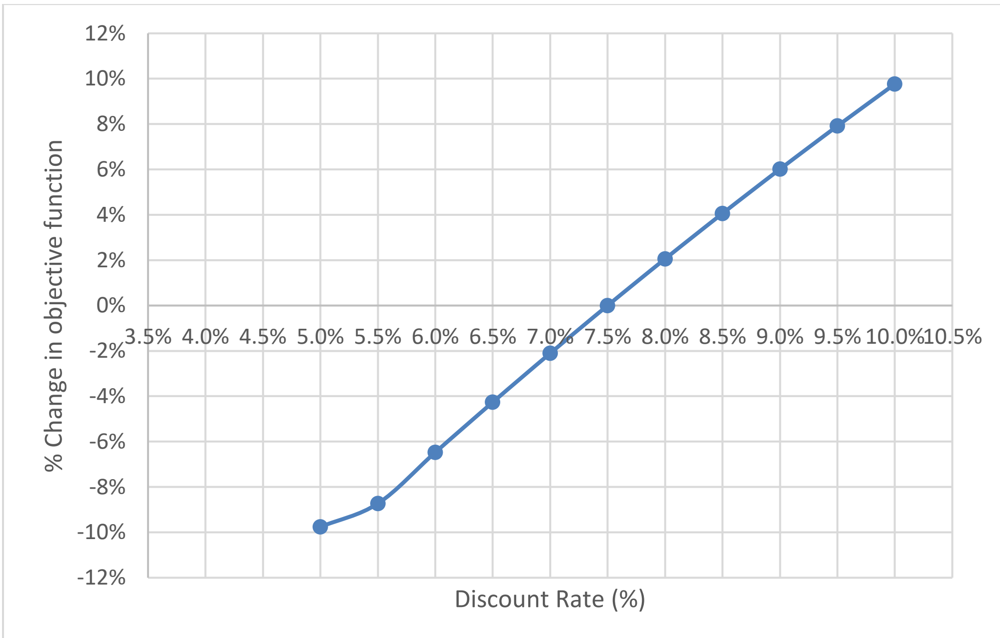


Figure 22 - Sensitivity Analysis of Discount Rate

5.2.3 Performance-related Parameters

Changing the yield parameters of products of ***MAD***, ***MADT***, ***GN***, ***INC***, ***SCO***, and ***SCG*** by ±30% had no effect on both the objective function and optimal processing pathway. This indicates the robustness of the pyrolysis pathway against a wide range of process efficiencies of the competing technologies. As far as pyrolysis products yields are concerned, an inverse proportion relationship exists between them and the objective function value. As shown in Figure 23, a 10% increase in bio-oil yield causes a 5% decrease in net cost and vice versa. However, at bio-oil yield reductions below 20%, the optimal pathway is changed to only filter press dewatering followed by thermal drying where the dried sludge can be sold as fertilizer causing no more additional reduction in net cots. A similar relationship exists between biochar yield and objective function value, however, a 10% increase in the yield causes a 6.7% reduction in the net cost. Biochar yield reduction increases the net cost also by 6.7% until the objective function reduction value stagnates at any yield reduction below 15% as shown in Figure 24. This indicates that the objective function value is more sensitive to changes in the biochar yield than bio-oil which is expected based on the sensitivity analysis results of products' selling prices as it was discussed in section 5.2.2.2.

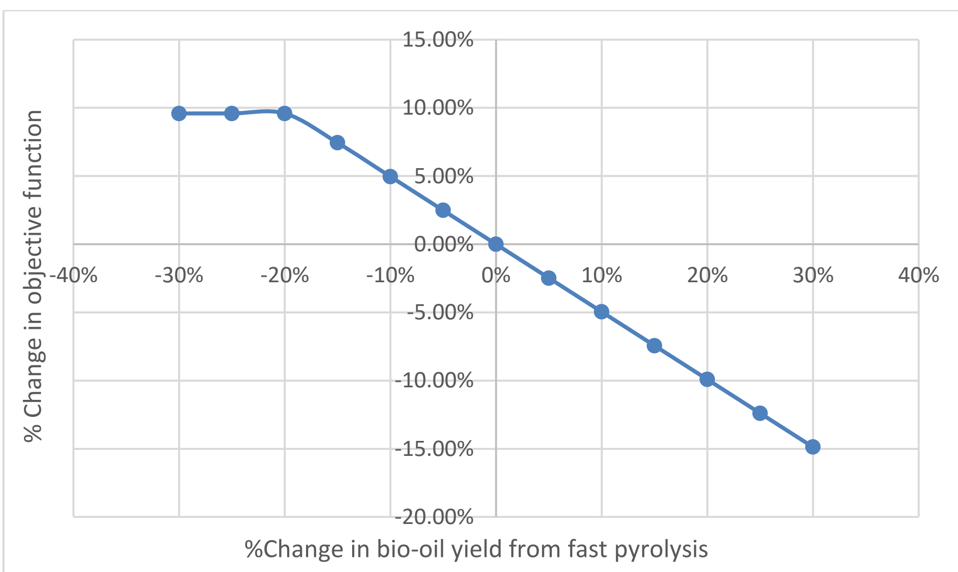


Figure 23 - Sensitivity Analysis of the Bio-oil Yield Parameter

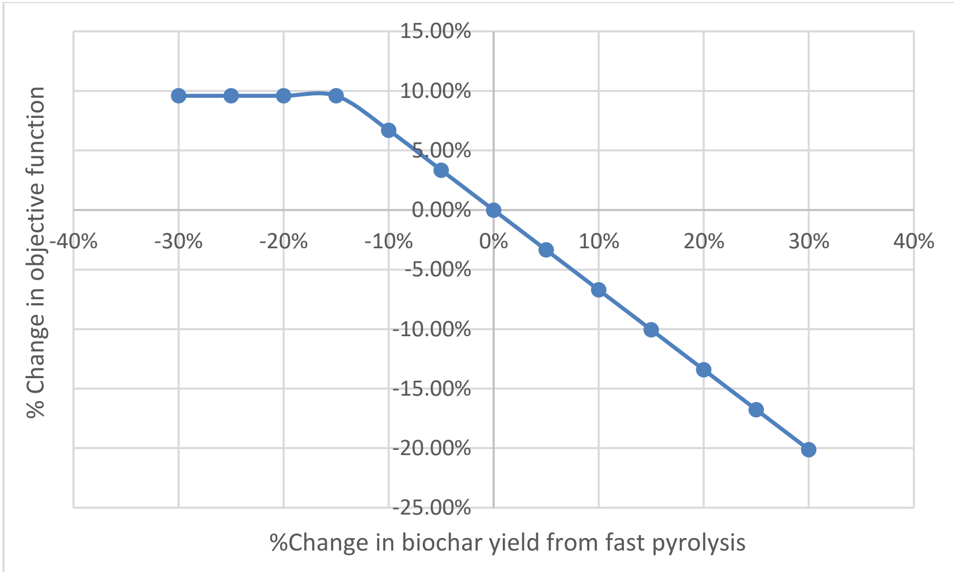


Figure 24 - Sensitivity Analysis of the Biochar Yield Parameter

The efficiency of dewatering processes was found to have an impact on the results. For belt dewatering, the assessed values were between 12% to 37% with a 5% increment. There is no change in results for dry solids% up to 22%. Starting from 27%, the optimal pathway favours a pathway of ***BPU*** followed by ***TD*** with the final product being Class A biosolids sold as fertilizers. Results for the latter three scenarios are listed in Table 19.

Table 19 – Sensitivity analysis results for belt press dewatering efficiency runs

PDS_{BP} **(Cases)**	**22% (and lower)**	**27%**	**32%**	**37%**
Optimal Pathway	***FPU+TD+PY***	***BPU + TD***	***BPU + TD***	***BPU + TD***
$TACC$ **(MM$/yr)**	3.21	1.84	1.72	1.62
TOC **(MM$/yr)**	9.77	4.54	4.03	3.67
$TREV$ **(MM$/yr)**	6.99	1.00	1.00	1.00
$NETCOST$ **(MM$/yr)**	5.99	5.37	4.75	4.28

The percentage of dry solids produced from filter press dewatering was varied between 27% to 48% with increments of 4%. The objective function value changed for all the assessed values. Optimal processing pathway swapped ***FPU*** in the base case results with ***BPU*** at outlet dry solids values between 27% to 35%. From 39% to 48%, the same pathway as that of the base case remained unchanged. Table 20 shows the summary of economic parameter values at those different values.

Table 20 – Sensitivity analysis results for filter press dewatering efficiency runs

PDS_{FP} (Cases)	35% (and lower)	39%	43%	48%
Optimal Pathway	BPU+TD+PY	FPU+TD+PY	FPU+TD+PY	FPU+TD+PY
$TACC$ **(MM$/yr)**	3.30	3.23	3.16	3.10
TOC **(MM$/yr)**	9.01	9.83	9.59	9.39
$TREV$ **(MM$/yr)**	6.08	6.99	6.99	6.99
$NETCOST$ **(MM$/yr)**	6.24	6.07	5.76	5.50

It can be concluded from the results of both dewatering processes that more efficient belt press dewatering can yield higher cost savings compared to filter press dewatering assuming the same capital and operating costs with the higher efficiency.

The final performance-related parameter studied was the LHV value of the sludge which could potentially have an impact on favouring the incineration technology at higher values. Nevertheless, even at an increase of 30% of LHV value, neither the objective function value nor the optimal pathway chosen had changed.

5.3 Further Analysis

It was observed from the results above that the following technologies had not been selected in any of the scenarios studied under the sensitivity analysis: ***MAD***, ***INC***, and ***SCO***. Hence, additional runs were performed on GAMS software to further investigate this. In each run, the binary variable z_i of one of these technologies was forced to equal 1 while all other conversion technologies z_i values were set to 0. Table 21 below lists the processing pathway resulting from each run as well as the change in the different components of the objective function compared to the base case scenario results. It is clearly evident from the results that the main driver for the lower objective function value of the base case scenario in comparison to the other three pathways is the higher annual revenues from selling biochar and bio-oil compared to electricity. In addition, there are no additional disposal costs required for pyrolysis products compared to the dewatered sludge from ***MAD*** and ash from ***INC*** and ***SCO*** that require transportation and disposal expenses. The operating and maintenance cost of all three pathways are significantly lower when compared to the base case, however, this does offset the remaining objective function components.

Table 21 - Additional Runs Results Summary

Processing Pathway	$\Delta\, TACC$	$\Delta\, TOC$	$\Delta\, TADC$	$\Delta\, TREV$	$\Delta\, NETCOST$
$MAD + FPD$	+0.80 MM$/yr [+25%]	-5.13 MM$/yr [-52%]	+3.17 MM$/yr [N/A]	-4.76 MM$/yr [-68%]	+3.65 MM$/yr [+61%]
$BPU + INC$	+0.68 MM$/yr [+21%]	-4.08 MM$/yr [-42%]	+0.78 MM$/yr [N/A]	-6.00 MM$/yr [-86%]	+3.37 MM$/yr [+56%]
$CU + SCO$	-0.01 MM$/yr [0%]	-5.20 MM$/yr [-53%]	+0.78 MM$/yr [N/A]	-5.45 MM$/yr [-78%]	+1.01 MM$/yr [+17%]

Chapter 6
Conclusion and Future Work

6.1 Conclusions

The main objective of this study was to propose a decision-making support tool for choosing the most economic pathway of sludge-to-energy technologies via superstructure optimization techniques. First, a brief review of promising candidate sludge-to-energy technologies was presented providing an overview of process descriptions, key reactions mechanisms, operating conditions, and parameters affecting process yields. The technologies reviewed were anaerobic digestion, incineration, gasification, pyrolysis, supercritical water oxidation and supercritical water gasification. Intermediate treatment processes like dewatering and thermal drying were also covered. Afterwards, a literature review was conducted to assess the state of research in the problem addressed and a gap was identified in utilizing mixed-integer optimization for sludge-to-energy decision-making frameworks. A mathematical model customized for the problem at hand was formulated and its applicability was tested via a case study for a hypothetical treatment facility with a capacity of 100 tDS/day.

One of the main conclusions from the case study is that although the model proposed was an MINLP formulation, which is usually difficult to solve, global optimal solutions were found efficiently within a reasonable CPU time of 70 seconds. The base case results showed that a combination of filter press dewatering followed by thermal drying and fast pyrolysis is deemed to be the most economic pathway in the available alternatives. The products of such pathway are bio-oil which can be used as an alternative fuel upon refining and biochar which has a variety of useful applications as an adsorption material or in agriculture. The estimated net specific cost for processing a tonne of dry sludge using this pathway was $180 which is in the same order of magnitude of current ranges of conventional sludge handling methods but with added environmental and social benefits.

The parameters used in the case study were roughly estimated from various sources in the literature and vendors that do not necessarily have a consistent basis for system boundaries and cost estimates methodologies/factors. Therefore, the model parameters defined in the case study were subjected to a high degree of uncertainty related to the reliability and availability of high-quality data in the literature as well as uncertainties related to the market volatility of the final product prices and government subsidies or incentives that can be provided to such products. Therefore, a sensitivity analysis for wide expected ranges of each of those uncertain parameters was conducted to determine the impact of each individual parameter variation on the objective function value represented by the annual net costs and/or changes in the optimal pathway that is selected by the model. It was found that:

- The technology selection route is sensitive to the capital cost parameter of ***MADT***, and operating costs of ***FPD*** and ***BPU***. Changes in the remainder of the technologies' capital and operating cost parameters did not impact the model results.
- Variations in the final products' prices also have a significant impact on the optimal pathway selected and the net costs of the selected plant. Electricity price is the most sensitive parameter followed by hydrogen and biochar prices, while bio-oil and class A biosolids (fertilizer) prices were found to be having the least relative effect on the objective function values.
- The objective function values were also found sensitive to the value of discount rates; however, the technology selection did not change with interest variations.
- Changing the yield parameters of technologies other than fast pyrolysis had no impact on the solution. This indicates the robustness of the pyrolysis pathway against a wide range of process efficiencies of the competing technologies.
- The objective function is highly sensitive to all the parameters related to the technologies in the base case optimal pathway, which proves the applicability of the proposed model and provides sensible results.
- The feed characteristics affected the optimal cost value which is explained by the economies of scale. The inverse relationship between net cost and process capacity effects starts to diminish at capacities above 200 tDS/day. There are slight impacts of changing the composition of the sewage sludge where cost reductions are observed at higher %VS due to increased yield of energy products correlated with an increase in organic contents of the sludge.

6.2 Future Work Directions

As far as the author's knowledge, this research is considered the first application of superstructure optimization methodology to sludge-to-energy decision making. Therefore, the main focus of the work was to lay the foundational pillars of such models to be able to compare the various technologies from an economic standpoint. This brings a lot of opportunities to further expand the scope of the proposed approach for future work directions such as:

- Accounting for the environmental impacts of each technology from a life cycle assessment point of view and embedding this as an additional criterion in selecting the technology other than economic criteria.
- Assessing the uncertainty of the parameters using a more robust method, such as stochastic optimization, considering the possible interactions between parameters variations in comparison to the one-parameter-at-a-time approach followed in this study.
- Extending the scope of the model such that it takes into account the whole supply chain of sludge in a certain geographic area allowing not only the selection of optimal technologies pathway but also the location of such facility taking into consideration the transportation of feed materials to the processing facility and final products to consumers.
- Exploring synergies of additional feedstock materials such as biomass or municipal solid wastes for co-processing with sludge.
- Evaluating the trade-offs between energy recovery pathways versus the recovery of valuable metals and/or nutrients from the sewage sludge.

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Appendix A
Model Sets Definition

Table 22 - Sets defining relationships between model blocks

i	$\mathbf{P}_i$	$\mathbf{S}_i$	$\mathbf{STF}_i$	$\mathbf{STPR}_i$
TH	N/A	{*MAD, MADT, CU, BPU, FPU*}	N/A	{THS}
MAD	{*TH*}	{*CD, BPD, FPD, E*}	{THS}	{ADS, E}
MADT	{*TH*}	{*CD, BPD, FPD, E*}	{THS}	{ADS, E}
CD	{*MAD, MADT*}	{SCO, SCG}	{ADS}	{DWS}
CU	{*TH*}	{SCO, SCG}	{THS}	{DWS}
BPD	{*MAD, MADT*}	{*TD, INC, GN, DS20*}	{ADS}	{DWS}
BPU	{*TH*}	{*TD, INC, GN*}	{THS}	{DWS}
FPD	{*MAD, MADT*}	{*TD, INC, GN, DS40*}	{ADS}	{DWS}
FPU	{*TH*}	{*TD, INC, GN*}	{THS}	{DWS}
TD	{*BPU, BPD, FPU, FPD*}	{*PY, FERT*}	{DWS}	{TDS}
INC	{*BPU, BPD, FPU, FPD*}	{*E, ASH*}	{DWS}	{E, ASH}
GN	{*BPU, BPD, FPU, FPD*}	{*E, ASH*}	{DWS}	{E, ASH}

i	$\mathbf{P}_i$	$\mathbf{S}_i$	$\mathbf{STF}_i$	$\mathbf{STPR}_i$
PY	*{TD}*	*{BO, BC}*	{TDS}	{BO, BC}
SCO	*{CU, CD}*	*{E, ASH}*	{DWS}	{E, ASH}
SCG	*{CU, CD}*	*{H2, ASH}*	{DWS}	{H2, ASH}

Table 23 - Sets defining component(s) of a specific stream s

s	$\mathbf{SCOMP}_s$
THS	{VS, ASH, DS, W}
ADS	{VS, ASH, DS, W}
E	{E}
P	N/A
L	N/A
FC	N/A
DWS	{VS, ASH, DS, W}
TDS	{VS, ASH, DS, W}
ASH	{ASH}

s	$\mathbf{SCOMP}_s$
BO	{BO}
BC	{BC}
H2	{H2}

Table 24 - Sets of component(s) used for specifying the revenue/disposal cost of a final product *i*

i	$\mathbf{FPCO}_i$
DS20	{DS}
DS40	{DS}
ASH	{ASH}
E	{E}
FERT	{DS}
BO	{BO}
BC	{BC}
H2	{H2}

Appendix B
GAMS Code

```
* Omar Morsy
* Sludge to Energy Superstructure Optimization

Sets
allitems 'all model items'
/TH,MAD, MADT, CD, CU, BPD,FPD, BPU, FPU, TD, INC, GN, PY,
          SCO, SCG, FERT, DS20, DS40, ASH, E, BO, BC, H2, THS,
         ADS, P, L, FC, DWS, TDS,
         VS, DS, W," "/
I(allitems)         'Combined set of Feed, process, and product blocks'
         /TH,MAD, MADT, CD, CU, BPD,FPD, BPU, FPU, TD, INC, GN, PY,
          SCO, SCG, FERT, DS20, DS40, ASH, E, BO, BC, H2/
FEED(I)      'Set for the feed blocks' /
         TH       "Thickened Sludge"       /
PROCESS(I)   'Set of processing blocks' /
         MAD      "Mesophilic Anaerobic Digestion"
         MADT     "MAD + Thermal Hydrolysis Pretreatment"
         CD       "Centrifuge dewatering for digested sludge"
         CU       "Centrifuge dewatering for undigested sludge"
         BPD      "Belt press dewatering for digested sludge"
         FPD      "Filter press dewatering for digested sludge"
         BPU      "Belt press dewatering for udigested sludge"
         FPU      "Filter press dewatering for udigested sludge"
         TD       "Thermal Drying Block"
         INC      "Incineration Block"
         GN       "Gasification block"
         PY       "Fast Pyrolysis"
         SCO      "Supercritical Water Oxidation"
         SCG      "Supercritical Water Gasification"
        /
AD(Process)      'Set of anaerobic digestion processes'
         /MAD, MADT/
```

```
CEN(PROCESS)       'Set of centrifugal dewatering options'
         /CD, CU/
BP(PROCESS)       'Set of belt press dewatering options'
         /BPD, BPU/
FP(PROCESS)       'Set of filter press dewatering options'
         /FPD, FPU/
DW(PROCESS)                'Set of all dewatering processes'
         /#BP, #FP, #CEN/
PRODUCT(I)  'Set of products blocks' /
         DS20     "20% dewatered digested sludge"
         DS40     "40% dewatered digested sludge"
         ASH      "Ash"
         E        "Electricity"
         FERT     "Class-A Biosolids (Fertilizer)"
         BO       "Bio-oil from pyrolysis"
         BC       "Biochar from pyrolysis"
         H2       "Hydrogen" /
DISP(PRODUCT)
/DS20, DS40, ASH/
REVP(PRODUCT)
/E, FERT, BO, BC,H2/ ;
alias    (i, j, k)                              ;
alias    (allitems,allitem,allit,alli)

*Connectivity between different blocks is described with the sets below:

Sets
S(I,J)   'Set of descendant block(s) J from block I'    /
         TH.(#AD, CU, BPU, FPU)
         #AD.(CD, BPD, FPD,E)
         #CEN.(SCO,SCG)
         BPD.(TD,GN,INC,DS20)
         FPD.(TD,GN,INC,DS40)
         (BPU,FPU).(TD,GN,INC)
         TD.(PY,FERT)
         (INC,GN).(ASH,E)
```

```
          PY.(BO,BC)
          SCO.(E,ASH)
          SCG.(H2,ASH)
/

P(I,K)    'Set of preceding block(s) K to another block I'    /
          (#AD, BPU, FPU,CU).TH
          (BPD,FPD,CD).#AD
          DS20.BPD
          DS40.FPD
          (TD,INC,GN).(#BP, #FP)
          (SCO,SCG).#CEN
          (FERT,PY).TD
          (BO,BC).PY
          E.(#AD,INC,SCO,GN)
          ASH.(INC,GN,SCO,SCG)
          H2.SCG
/


*Process streams and componenets

STREAM(allitems)    'Set of process streams' /
          THS      "Thickened Sludge"
          ADS      "Anaerobically Digested Sludge"
          E        "Electricity"
          P        "Polymer for conditioning"
          L        "Lime for conditioning"
          FC       "Ferric Chloride for conditioning"
          DWS      "Dewatered Sludge"
          TDS      "Thermally dried sludge"
          ASH      "Ash"
          BO       "Bio-oil from pyrolysis"
          BC       "Biochar from pyrolysis"
          H2       "Hydrogen" /
```

```
CHEM(Stream)     'Set of chemicals for conditioning'
         /P, L, FC/
COMP(allitems)     'Set of components of process streams' /
         VS       "Total volatile solids"
         ASH      "Ash (minerals, chemicals for conditioning, etc."
         DS       "VS + Ash"
         W        "Water or moisture in the sludge/biosolids"
         E        "Electricity"
         BO       "Bio-oil from pyrolysis"
         BC       "Biochar from pyrolysis"
         H2       "Hydrogen"
/

*Streams exiting from a certain block
STF(I,stream)    'Set of matching feed streams with processes'
/(#AD,BPU,FPU,CU).THS, (BPD,FPD,CD).ADS,
(TD,INC,GN,SCO,SCG,DS20,DS40).DWS, E.E, ASH.ASH,
(FERT,PY).TDS, BO.BO, BC.BC, H2.H2 /

STPR(I,stream)     'Set of matching product streams with processes'
/ TH.THS, #AD.(ADS,E), #DW.DWS, TD.TDS, (INC,GN).(E,ASH), PY.(BO,BC),
SCO.(E,ASH), SCG.(H2,ASH)/

SCOMP(stream,comp) 'set of components applicable to a certain stream'
/THS.(VS,ASH,DS,W), ADS.(VS,ASH ,DS,W),E.E, DWS.(VS,ASH,DS,W),
TDS.(VS,ASH,DS,W), ASH.ASH, BO.BO, BC.BC, H2.H2/


CHDW(CHEM,DW)    'Set matching chemicals added to dewatering options'
/P.(#CEN,#BP), (FC,L).#FP/


FPCO(product,comp) 'set of comp in specifiying a product revenue/disposal
cost'
/E.E, (DS20, DS40).DS, FERT.DS, ASH.ASH, BO.BO, BC.BC, H2.H2 /  ;
```

Scalars

```
FTHS      "Feed thickened sludge flow in tonnes of dry solids per day
(tDS/day)"
          /100/
FPVS      "Percentage of volatile solids in the feed thickened sludge"
          /0.7/
FPASH     "Percentage of ash in the feed thickened sludge"
          /0.3/
LHV_VS    'LHV of volatile solids in sludge in MJ/tonneVS'
          /21000/
Lambda_W 'latent heat of vaporization of water in MJ/tonneH2O'
          /2260/
MJ2kWh    /0.27778/
HLF       'Heat loss factor in incinerator'
          /0.05/
Eff_R     'Efficiency of rankine cycle'
          /0.25/
YBO       /1/
YBC       /1/
DPY       "Number of operating days per year"
          /333/
n         "Number of years for the project lifetime"
          /20/
d         "Interest/discount rate"
          /0.075/
AF        Anuualized cost factor
SAC       "Specific annual cost (USD per tonne of sludge)"   ;

AF = (d*(1+d)**n)/((1+d)**n-1);
```

Parameters

```
PDS(I)                    Percentage of dry solids out of a certain block
```

```
                         /TH    0.05, #CEN  0.1, #BP  0.2, #FP  0.4, TD
0.9/
VSD(PROCESS)             Volatile solids destruction in AD
                         /MAD    0.5, MADT    0.6/
Y(PRODUCT, PROCESS)      Yield of a certain product from a certain process
                         /E.MAD   2390
                          E.MADT  2390, E.GN  1368, E.SCO  825, H2.SCG
112/

*Yield of elec. in MAD / MADT is in kWh/tVS destructed
cap(process)             Design capacity of a process
                         /MAD 200 ,MADT  200,#DW 200, TD 200, INC 200, GN
200
                          PY 200, SCO 200, SCG 200/
BCC(Process)           Base capital cost of a certain process in million
USD (2019)
BQ(Process)            Base capacity in capital cost calculation
alpha(Process)         Economies of scale exponent
                         /MAD    0.6, MADT   0.6, #DW 0.6, TD 0.6, INC
0.6, GN  0.6, PY  0.6, SCO  0.6, SCG 0.6/
POC(Process)           Operating cost parameter for a certain process
SP(Product)            Price of selling a certain prodcut
DC(Product)            Disposal cost for a certain product
DR(CHEM)               Dosage rate of a certain chemical tonne per tonne
of DS
                         /P    0.004, L    0.1, FC    0.07/ ;

$onEcho > ParametersList.txt
par=BCC rng=Parameters!A4:F17 rdim=1 cdim=0 ignoreColumns=B,C,D,E
par=POC rng=Parameters!A20:F33 rdim=1 cdim=0 ignoreColumns=B,C,D,E
par=BQ rng=Parameters!A4:G17 rdim=1 cdim=0 ignoreColumns=B,C,D,E,F
par=SP rng=Parameters!A36:B43 rdim=1 cdim=0
par=DC rng=Parameters!A36:C43 rdim=1 cdim=0 ignoreColumns=B
$offEcho

$call gdxxrw.exe C:\Users\oumorsy\Documents\gamsdir\S2ESSORev0.xlsx
```

```
@ParametersList.txt
$gdxin S2ESSORev0.gdx
$LOAD  BCC POC BQ SP DC
$gdxin

Positive variables
*Process Variables
FI(Stream, Comp, I)        'Total inlet flowrate of a component within a
process stream into block I'
FO(Stream, Comp, I)        'Total outlet flowrate of a component within a
process stream into block I'
FPI(Product)               'Total flowrate of a final product'
x(Stream,Comp,I,J)         'Flowrate of a component within a process stream
from block I to J'
SF(Stream,I,J)             'Split factor of a stream from block I to J'
CH(CHEM,DW)                Chemical additive stream
FWE                        'Flow of water evaporated in TD block'
H_VS                       'Heat flow of volatile solids entering
incineration block'
H_W                       'Heat required to evaporate moisture in sludge
entering incineration block'
H_INC                      'Net heat recovered from incineration'
*Economic variables
CC(Process)                'Capital cost of a certain process in million USD
(2019)'
ACC(Process)               'Annualized Capital Cost of a certain process'
OC(Process)                'Annual perating cost of a certain process'
ADC(DISP)                Annual disposal costs of a certain final product
TACC                       Annulaized capital costs
TADC                       Total annual disposal costs
TOC                        Total operating costs
costs                      Annual total costs
RP(REVP)                 Revenues from sales of a certain final product
Rev                        total revenues
;
```

```
SF.up(Stream,I,J) = 1;
SF.fx(Stream,I,J)$(not STF(J,stream)) = 0;

Variables
netcost        Net cost of chosen pathway;


Binary variable
Z(process)        "Binary variable that dictates whether a certain process
exists or not";


Equations

*General Equations

GEQ1(process,stream,comp)        Total Inlet flowrate of a component c in
stream s entering a certain process
GEQ2(process,j,stream,comp)      Individual component c in stream s from
process i to descendant process j
GEQ3(process,stream,comp)        Total outlet flowrate of a component c in
stream s entering a certain process
GEQ4(process,stream)             Summation of split factors of process i
in relation to integer variable z(i)
GEQ5(process,stream,comp)        Upper bound on inlet flowrate to process
i
GEQ6(process,stream,comp)        Lower bound on inlet flowrate to process
i;

*GEQ3B.lo(process,j,stream) = 0;

GEQ1(process,stream,comp)$((STF(process,stream) and SCOMP(stream,comp))
..
FI(stream,comp,process) =e= sum(k$P(process,k),x(stream,comp,k,process));
```

```
GEQ2(process,j,stream,comp)$((STPR(process,stream) and S(process,j) and
SCOMP(stream,comp))) ..
x(stream,comp,process,J) =e= SF(stream,process,J) *
FO(stream,comp,process) ;

GEQ3(process,stream,comp)$((STPR(process,stream) and SCOMP(stream,comp)))
..
FO(stream,comp,process) =e= sum(j$S(process,j),x(stream,comp,process,J)) ;

GEQ4(process,stream)$STPR(process,stream) ..
sum(j$(S(process,j)),SF(stream,process,J)) =e= z(process);

GEQ5(process,stream,comp)$STF(process,stream) ..
FI(stream,'DS',process) =l= z(process) * cap(process);

GEQ6(process,stream,comp)$STF(process,stream) ..
FI(stream,'DS',process) =g= 0.1 * z(process) * cap(process);


*TH Block Modeling
Equations
TH1      Total flowrate of VS in THS stream exiting TH block
TH2      Total flowrate of ASH in THS stream exiting TH block
TH3      Total flowrate of DS in THS stream exiting TH block
TH4(J)   Flowrate of VS in THS stream going to any descendant block J
TH5(J)   Flowrate of ASH in THS stream going to any descendant block J
TH6(J)   Flowrate of total dry solids in THS to any descendant block J
TH7(J)   "Flowrate of water/mositure in THS to any descendant block J"
TH8      Split factor summation to 1;


TH1 .. FO('THS','VS','TH') =e= FPVS * FTHS;
TH2 .. FO('THS','ASH','TH') =e= FPASH * FTHS;
TH3 .. FO('THS','DS','TH') =e= FTHS;
TH4(J)$S('TH',J) .. x('THS','VS','TH',J) =e= SF('THS','TH',J) *
FO('THS','VS','TH');
```

```
TH5(J)$S('TH',J) .. x('THS','ASH','TH',J) =e= SF('THS','TH',J) *
FO('THS','ASH','TH');
TH6(J)$S('TH',J) .. x('THS','DS','TH',J) =e= x('THS','VS','TH',J) +
x('THS','ASH','TH',J);
TH7(J)$S('TH',J) ..
x('THS','W','TH',J) =e= x('THS','DS','TH',J) * ((1-PDS('TH'))/PDS('TH'));
TH8 .. sum(J$S('TH',J), SF('THS','TH',J)) =e= 1;

*AD Blocks Modeling
Equations

AD1(AD)      Total flowrate of VS in ADS exiting an AD block
AD2(AD)      Total flowrate of ASH in ADS exiting an AD block
AD3(AD)      Total flowrate of DS in ADS exiting an AD block
AD4(AD)      Net elecricity produced from an AD block
*Economic modeling of MAD
EAD1(AD)     Capital cost of MAD
EAD2(AD)     Operating cost of MAD ;

AD1(AD) .. FO('ADS','VS',AD) =e= FI('THS','VS',AD) * (1-VSD(AD));
AD2(AD) .. FO('ADS','ASH',AD) =e= FI('THS','ASH',AD);
AD3(AD) .. FO('ADS','DS',AD) =e= FO('ADS','VS',AD) + FO('ADS','ASH',AD);
AD4(AD) .. FO('E','E',AD) =e= FI('THS','VS',AD) * VSD(AD) * Y('E',AD);

EAD1(AD) .. CC(AD) =e= BCC(AD) * ( FI('THS','DS',AD) / BQ(AD))**alpha(AD);
EAD2(AD) .. OC(AD) =e= POC(AD) * FI('THS','DS',AD) * DPY;

*Dewatering blocks modeling
Equations

DW1(CHEM,DW)     flowrate of chemical for chemical conditioning
DW2(DW)          volatile solids mass balance
DW3(DW)          Ash mass balance
DW4(DW)          Dry solids mass balance
DW5(DW)          moisture mass balance
```

```
*Economic modeling of DW
EDW1(DW,stream)     Capital cost of DW
EDW2(DW,stream)     Operating cost of DW ;

DW1(CHEM,DW)$(CHDW(CHEM,DW)) .. CH(CHEM,DW) =e= sum(stream$STF(DW,
stream),FI(stream,'DS',DW)) * DR(CHEM);
DW2(DW) .. FO('DWS','VS',DW) =e= sum(stream$STF(DW,
stream),FI(stream,'VS',DW));
DW3(DW) .. FO('DWS','ASH',DW) =e= sum(stream$STF(DW,
stream),FI(stream,'ASH',DW)) + sum(CHEM$CHDW(CHEM,DW),CH(CHEM,DW));
DW4(DW) .. FO('DWS','DS',DW) =e= FO('DWS','VS',DW) + FO('DWS','ASH',DW);
DW5(DW) .. FO('DWS','W',DW) =e=  FO('DWS','DS',DW) * ((1-
PDS(DW))/PDS(DW));

EDW1(DW,stream)$(STF(DW, stream)) .. CC(DW) =e= BCC(DW) * (
FI(stream,'DS',DW) / BQ(DW))**alpha(DW);
EDW2(DW,stream)$(STF(DW, stream)) .. OC(DW) =e= POC(DW) *
FI(stream,'DS',DW) * DPY;

*Thermal Drying block modeling
Equations

TD1               Total flowrate of VS in the TDS stream existing from TD
block
TD2               Total flowrate of ASH in the TDS stream existing from TD
block
TD3               Total flowrate of DS in the TDS stream existing from TD
block
TD4               Total flowrate of moisture in the TDS stream existing
from TD block
TD5               Total flowrate of water evaporated

*Economic modeling of TD
ETD1              Capital cost of DW
ETD2              Operating cost of DW ;
```

```
TD1 .. FO('TDS','VS','TD') =e= FI('DWS','VS','TD');
TD2 .. FO('TDS','ASH','TD') =e= FI('DWS','ASH','TD');
TD3 .. FO('TDS','DS','TD') =e= FI('DWS','DS','TD');
TD4 .. FO('TDS','W','TD') =e= FO('TDS','DS','TD') * ((1-
PDS('TD'))/PDS('TD'));
TD5 .. FWE =e= FI('DWS','W','TD') - FO('TDS','W','TD');

ETD1.. CC('TD') =e= BCC('TD') * ( FWE / BQ('TD'))**alpha('TD');
ETD2 .. OC('TD') =e= POC('TD') * FWE * DPY;

*Incineration Block Modeling
Equations
INC1                Total ash flowrate out of incineration block
INC2                Latent heat to be recovered from volatile solids entering
INC
INC3                Heat of vaporization of moisture entering the inc block
INC4                Net heat recovered from icineration block
INC5                Net electricity produced from incineration

EINC1
EINC2;

INC1 .. FO('ASH','ASH','INC') =e= FI('DWS','ASH','INC');
INC2 .. H_VS =e= LHV_VS * MJ2kWh * FI('DWS','VS','INC') ;
INC3 .. H_W =e= Lambda_W * MJ2kWh * FI('DWS','W','INC') ;
INC4 .. H_INC =e= (H_VS - H_W) * (1 - HLF);
INC5 .. FO('E','E','INC') =e= H_INC * eff_r;

EINC1.. CC('INC') =e= BCC('INC') * ( FI('DWS','DS','INC') /
BQ('INC'))**alpha('INC') + (9/10000)*((x('E','E','INC','E')**0.695));
EINC2 .. OC('INC') =e= (POC('INC') * FI('DWS','DS','INC') * DPY) +
(x('E','E','INC','E')*0.018*DPY) ;

*Gasification Block Modeling
Equations
GN1               Total ash flowrate out of gasification block
```

```
GN2              Net electricity produced from gasification

EGN1
EGN2 ;

GN1 .. FO('ASH','ASH','GN') =e= FI('DWS','ASH','GN');
GN2 .. FO('E','E','GN') =e= FI('DWS','VS','GN') * Y('E','GN');

EGN1.. CC('GN') =e= BCC('GN') * ( FI('DWS','DS','GN') /
BQ('GN'))**alpha('GN');
EGN2 .. OC('GN') =e= (POC('GN') * FI('DWS','DS','GN') * DPY);

*Pyrolysis Block Modeling
Equations
PY1              Total Bio-oil flowrate out of pyrolysis block
PY2              Total Bio-char flowrate out of pyrolysis block

EPY1
EPY2;

PY1 .. FO('BO','BO','PY') =e= YBO*(0.6368 * FI('TDS','VS','PY') - 0.1134 *
FI('TDS','DS','PY'));
PY2 .. FO('BC','BC','PY') =e= YBC*(-0.7895 * FI('TDS','VS','PY') + 0.9879
* FI('TDS','DS','PY'));


EPY1.. CC('PY') =e= BCC('PY') * ( FI('TDS','DS','PY') /
BQ('PY'))**alpha('PY');
EPY2 .. OC('PY') =e= (POC('PY') * FI('TDS','DS','PY') * DPY);

*SCWO Block Modeling
Equations
SCO1              Net electricity produced from SCWO
SCO2              Ash product leaving SCWO

ESCO1
```

```
ESCO2;

SCO1 .. FO('E','E','SCO') =e= FI('DWS','VS','SCO') * Y('E','SCO');
SCO2 .. FO('ASH','ASH','SCO') =e= FI('DWS','ASH','SCO');

ESCO1.. CC('SCO') =e= BCC('SCO') * ( FI('DWS','DS','SCO') /
BQ('SCO'))**alpha('SCO');
ESCO2 .. OC('SCO') =e= (POC('SCO') * FI('DWS','VS','SCO') * DPY);

*SCWG Block Modeling
Equations
SCG2            Hydrogen produced from SCWG
SCG3            Ash product leaving SCWG

ESCG1
ESCG2;
SCG2 .. FO('H2','H2','SCG') =e= FI('DWS','VS','SCG') * Y('H2','SCG');
SCG3 .. FO('ASH','ASH','SCG') =e= FI('DWS','ASH','SCG');

ESCG1.. CC('SCG') =e= BCC('SCG') * ( FI('DWS','DS','SCG') /
BQ('SCG'))**alpha('SCG');
ESCG2 .. OC('SCG') =e= (POC('SCG') * FI('DWS','DS','SCG') * DPY);

*General economic modeling
Equations

FPROD(Product)            Total flowrate of final products
EACC(Process)             Anuualized capital cost of each process
EADC(DISP)              Annual disposal costs of each product
ETACC                     Total anuualized capital cost of all chosen
processes
ETOC                      Total operating costs for chosen processes
ETADC                     Total disposal costs per year
ERP(REVP)               "Annual sales / revenue of each product"
ECosts                    Total annual costs
Revenue                   Revenue from sales of all products
```

```
ENETCOST                    objective function


;

FPROD(Product) .. FPI(Product) =e=
sum(K$P(Product,K),sum(stream$STF(product,stream),sum(comp$FPCO(product,co
mp),x(stream,comp,K,product))));


EACC(Process) .. ACC(process) =e= CC(process) *  AF;
EADC(DISP) .. ADC(DISP) =e= FPI(DISP)*DPY*DC(DISP);
ETACC .. TACC =e= sum(PROCESS, Z(Process) * ACC(Process));
ETOC .. TOC =e= sum(PROCESS, Z(Process) * OC(Process));
ETADC .. TADC =e= sum(DISP, ADC(DISP));

ERP(REVP) .. RP(REVP) =e= FPI(REVP)*DPY*SP(REVP);
ECosts .. costs =e= TACC + TOC + TADC;
Revenue .. rev =e= sum(REVP, RP(REVP));
ENETCOST .. netcost =e= costs - rev;



model sludgetoenergy /all/;

option limrow=40
optca=1e-6,
optcr=1e-6; solve sludgetoenergy using MINLP minimizing netcost;



SAC = netcost.l / (FTHS *DPY);
Display AF, SAC;
```