KTH Industrial Engineering
and Management

Feasibility Study for Production of Biogas from Wastewater and Sewage Sludge - Development of a Sustainability Assessment Framework and its Application

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Abstract

Clean water and renewable energy are essential requirements to build resilience towards the adverse effects of climate change and global warming. Advanced wastewater treatment options may provide a unique opportunity to recover various useful resources such as energy (biogas), fertilizers, minerals, and metals embedded in the wastewater stream. However, considerable challenges remain when it comes to designing and planning sustainable wastewater treatment systems. This thesis focuses on the avenues of energy recovery from wastewater treatment plants (WWTP), by evaluating the potential for biogas recovery from wastewater and sewage sludge treatment in WWTPs. Various available technologies for biogas recovery are examined and evaluated to understand their viability in different applications and relative performance. Further, the methodologies and tools employed to assess such energy recovery systems are evaluated, covering the technical, economic, and environmental performance aspects. A sustainability assessment framework is then developed, using appropriate sustainability indicators to assess performance. The framework is applied to a case study of a WWTP in the emerging city of Tbilisi, Georgia. A spreadsheet tool is also developed to aid the sustainability (technoeconomic and environmental) assessments for the case study. The case study results reveal a significant biogas recovery potential, with annual energy generation potential of 130 GWh from combined heat and power (CHP) recovery, and a potential to avoid 28,200 tCO_{2eq} emissions every year, when biogas is recovered only from the wastewater. The recovery potential increases when biogas is recovered from both wastewater and sewage sludge. Further, the contribution of overall resource (energy and nutrient) recovery in WWTPs to the Sustainable Development Goals is examined. By studying the linkage of various benefits to the different SDGs, the multilateral and cross-cutting nature of benefits from resource recovery is clearly illustrated. The thesis concludes with the discussion of possible future technologies and perspectives that can enhance the sustainability of WWTPs and help transform them into Wastewater Resource Recovery Facilities (WRRFs).

Keywords: resource recovery, wastewater treatment, biogas, anaerobic digestion, energy recovery, sustainability assessment, SDG

Sammanfattning

Rent vatten och förnybar energi är väsentliga krav för att bygga motståndskraft mot de negativa effekterna av klimatförändringar och global uppvärmning. Avancerade avloppsreningsalternativ kan ge en unik möjlighet att återvinna olika användbara resurser som energi (biogas), gödselmedel, mineraler och metaller inbäddade i avloppsvatten strömmen. Det finns emellertid stora utmaningar när det gäller att utforma och planera hållbara reningssystem. Denna avhandling fokuserar på möjligheterna till energiåtervinning från avloppsreningsverk (WWTP), genom att utvärdera potentialen för biogasåtervinning från avloppsvatten- och avloppssrening i WWTP. Olika tillgängliga tekniker för återvinning av biogas undersöks och utvärderas för att förstå deras livskraft i olika applikationer och relativa prestanda. Vidare utvärderas de metoder och verktyg som används för att utvärdera sådana system för energiåtervinning som täcker de tekniska, ekonomiska och miljömässiga aspekterna. En ram för hållbarhetsbedömning utvecklas sedan med hjälp av lämpliga hållbarhetsindikatorer för att bedöma prestanda. Ramverket tillämpas på en fallstudie av en WWTP i den framväxande staden Tbilisi, Georgien. Ett kalkylarkverktyg utvecklas också för att underlätta bedömningarna av hållbarhet (teknisk ekonomi och miljö) för fallstudien. Resultaten från fallstudien avslöjar en betydande återvinningspotential för biogas, med en årlig energiproduktions potential på 130 GWh från kombinerad värme och kraft (CHP), och en potential att undvika 28.200 ton CO2-utsläpp varje år, när biogas endast återvinns från avloppsvattnet. Återvinningspotentialen ökar när biogas utvinns från både avloppsvatten och avloppsslam. Vidare undersöks bidraget från den totala återhämtningen av energi (energi och näringsämnen) i WWTP till målen för hållbar utveckling. Genom att studera kopplingen mellan olika fördelar till de olika SDG: erna illustreras den multilaterala och tvärgående karaktären av fördelarna med resursåtervinning. Avhandlingen avslutas med diskussionen om möjliga framtida tekniker och perspektiv som kan förbättra WWTP: s hållbarhet och hjälpa till att omvandla dem till anläggning för återvinning av resurser från avloppsvatten.

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Akash Som Gupta

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Abbreviations

ABR	Anaerobic Baffled Reactor
AD	Anaerobic Digestion
AnMBR	Anaerobic Membrane BioReactor
BioCNG	Bio Compressed Natural Gas
BMP	Biochemical Methane Potential
BOD	Biological Oxygen Demand
CAS	Conventional Activated Sludge
CBA	Cost-Benefit analysis
CDM	Clean Development Mechanism
CHP	Combined Heat and Power
COD	Chemical Oxygen Demand
CSTR	Continuous Stirred Tank Reactor
EGSB	Expanded Granular Sludge Bed
EIA	Environmental Impact Assessment
EU-WFD	European Union- Water Framework Directive
FOG	Fats, Oils, and Grease
HRT	Hydraulic Retention Time
IRR	Internal Rate of Return
IWMI	International Water Management Institute
IWRM	Integrated Water Resources Management
LCA	Life-Cycle Assessment
MCDA/M	Multi-Criteria Decision Analysis/ Decision-Making
NEW Factory	Nutrient, Energy, Water Factory
NPV	Net Present Value
OFMSW	Organic Fraction of Municipal Solid Waste
PS	Primary Sludge
SDG	Sustainable Development Goals
SRT	Solids Retention Time
SS	Suspended Solids
TS	Total solids
DS	Dry solids
VS	Volatile solids
TPAD	Temperature Phased Anaerobic Digestion
UASB	Upflow Anaerobic Sludge Blanket Reactor
UN-WWAP	United Nations- World Water Assessment Programme
WAS	Waste Activated Sludge
WERF	Water Environment Research Foundation
WRRF	Water Resource Recovery Facilities
WWTP	Wastewater Treatment Plant

Glossary

Circular economy - A circular economy is primarily based upon the idea of designing out waste as well as pollution, keeping materials and products in use thereby regenerating natural systems.

Freshwater - Freshwater can be defined as water that is not salty, i.e., water found in lakes rivers streams, etc. freshwater can also be termed as water containing minimum quantities of dissolved salts, thus distinguishing it from seawater. All freshwater ultimately comes from the precipitation of atmospheric water vapor reaching inland lakes, rivers as well as groundwater bodies directly, or due to melting of snow or ice.

Resource recovery - Resource recovery in relation to waste can be defined as reusing the waste OR Recycling the waste OR Recovering energy and other resources from the waste.

Domestic wastewater - It is the wastewater originating from human activities such as washing, bathing, food preparation, restrooms, and laundry.

Sewage sludge - Can be defined as the final solid component produced as a byproduct of wastewater treatment.

Biogas - Biogas is a gas produced when organic matter breaks down in the absence of oxygen. It is a combination of primarily methane, carbon dioxide, and water vapour, and can be used as a fuel.

Digestate - Digestate is a nutrient-rich substance remaining after the anaerobic digestion of a biodegradable feedstock that can be used as a fertilizer. Digestate mainly comprises of leftover indigestible materials as well as dead microorganisms.

Anaerobic Digestion - A series of biological processes that involve microbial breakdown of biodegradable material in the absence of oxygen.

Biorefinery - a refinery that involves sustainable processing of biomass into a spectrum of biobased products (such as feed, food materials, and chemicals); as well as bioenergy (Biofuels, power and/or heat/ energy)

Sludge stabilization - is the process of reducing sludge odour, putrescence, and presence of pathogenic organisms from sludge.

1 Introduction

"A happy man is too satisfied with the present to dwell too much on the future."

- Albert Einstein

While Einstein wrote this in a high school essay called "My Future Plans", the quotation from the famed scientist is apt for the situation in today's society. The incredible economic and industrial growth in the past couple of centuries has seen human society reach new frontiers of science and technology, while providing the necessary resources for a comfortable and abundant lifestyle for an increasing portion of the global population. These fuels are still powering everything from our homes to our ships today, and we have only become increasingly dependent on them with time. The question that looms now is how long we can continue on this path of wanton consumption and use our natural resources in such indiscriminate manner. The need for renewable sources of energy and sustainable consumption of resources is imminent on today's society to prevent the catastrophic effects of global warming, and to maintain a habitable and sufficient future for the coming generations (Amulya et al., 2016).

With growing consensus amongst global leaders and policymakers about the importance of sustainable development, the focus is on shifting to low-carbon societies and Circular Economy as primary economic and environmental ideologies. The Circular Economy is defined as "a regenerative system which minimizes resource input and wastage, emissions, and energy usage and leakage by slowing, closing, and narrowing energy and material loops" (Geissdoerfer et al., 2017) This implies a focus on reducing waste to a minimum, and recovering useful resources from the waste streams generated from social and industrial activity. These recovered resources can be further used in the economy, thereby creating more value for the stakeholders. The concept of Circular Economy has been recognized globally, with policymakers and governing agencies integrating it into local, national, and international policies. The extensive European Circular Economy Package is a good evidence of the increasing importance of this concept (European Commission, 2018).

In line with the concepts of sustainable development and circular economy, this research thesis explores the avenues of resource recovery from Wastewater Treatment Plants (WWTPs). As an essential public service utility in urban areas, WWTPs present a unique opportunity to recover important resources such as energy, nutrients, bio-fertilizers, among others, while improving the treatment levels of wastewater and sludge effluents that are let back into the ecological system (Bachmann, 2015). The thesis reviews the potential benefits of energy and resource recovery from WWTPs, and develops an assessment tool for evaluating the technical, economic, and ecological feasibility of recovering energy in the form of biogas from wastewater and sludge in WWTPs. It is aimed at energy and sustainable development policymakers and WWTP operators in developing nations, and provides them with a tool to assess the potential for recovering biogas. The thesis allows stakeholders to get an insight into the feasibility of pursuing energy recovery in their local context.

1.1 Background information and problem statement

Water is one of the fundamental natural resources required by living organisms to survive. For human society, access to clean water, efficient sanitation and water treatment are considered basic human rights (UN Economic and Social Council, 2003). While there are high quality water services available in developed countries, there is still a dire need for effective water resource management, good sanitation, and sustainable wastewater treatment in developing nations around the world. In 2015, 32% of global population was still lacking wastewater treatment and sanitation facilities (WHO-UNICEF JMP, 2017). Wastewater from urban settlements and industries is one of the major sources of contamination for water reservoirs. Wastewater management poses a vital problem for existing wastewater treatment plants (WWTPs) as urbanization increases, thereby increasing the volume of wastewater produced (Maragkaki, et al. 2018; Bachmann 2015). While being an important natural resource, water also transports energy and other resources. Anthropogenic activity adds chemicals, materials, and energy by way of usage, consumption, and generation of wastewater from industrial and urban centres. Therefore, the urban water chain presents a feasible opportunity for resource recovery and closing the loop on energy and nutrient cycles (Van Der Hoek et al., 2016)

Resource recovery from wastewater has multiple advantages, as it can reduce downstream pollution of water sources, reduce greenhouse gas (GHG) emissions, improve the economics and profitability of the WWTP, as well as improve the quality of life for the concerned populations (Lynd et al., 2008), thereby encompassing all three dimensions of sustainable development: environmental, economic, and social. Biogas is an interesting energy resource that can be recovered from wastewater, as it can be used internally in the WWTP for generating heat and electric power, and has the potential for upgradation and further use as a transport fuel (Venkatesh and Elmi, 2013). It is an important by-product produced in WWTPs during the biological treatment of wastewater and sewage sludge, and is strategically placed at the nexus of energy, water, and solid wastes. Thus, biogas production from anaerobic digestion offers multiple advantages including effective sludge management and minimizing sludge generation, while providing an important bio-fuel as a by-product, reducing the GHG emissions, and closing the carbon nutrient cycles (Maragkaki et al., 2018).

While there has been considerable research and study on energy and resource recovery from wastewater, significant challenges remain in developing countries when it comes to designing and implementing sustainable wastewater systems. A major challenge is the lack of systemic planning and design methodologies, that can take into consideration the various socio-technical and economic factors that interplay in developing countries, and help design and deploy the most suitable resource recovery solution for a given cultural and geographical context (Guest, et al. 2009). Several studies have been conducted on assessing the techno-economic or environmental feasibility of recovering resource such as biogas from WWTPs in developed countries, but there has been a lack of similar analysis for developing countries with a low level of sewage treatment (dos Santos et al., 2016a). There is a scope for developing easily deployable tools that can serve as a first step for decision making by providing useful data for various technological options. Such tools can help grassroots level planners in developing countries to get preliminary process data for different technologies, and use this in conjunction with other social and local considerations to design well-suited wastewater treatment systems.

This thesis is in response to this requirement of effective and all-round assessment tools and methodologies that can help improve the implementation of resource recovery technologies (e.g. biogas recovery) in developing countries. The thesis first qualitatively reviews the benefits of sustainable resource recovery from WWTPs and maps the possible contributions to Sustainable Development Goals (SDGs) (chapter 3). Next, the thesis focuses on energy recovery through biogas generation, and follows a technical examination of biogas recovery technologies and the methods used to assess biogas recovery systems (chapter 4 - 5). Lastly, a quantitative sustainability assessment framework for biogas recovery from WWTPs is developed based on widely used sustainability indicators (chapter 6). By creating an assessment tool to evaluate biogas production potential, econometric parameters like Net Present Value and Internal Rate of Revenue, and greenhouse gas emission reductions for various technological options, a preliminary snapshot of the overall performance of the chosen technological pathway can be obtained. The developed tool is then utilised in a case study based in a Georgian WWTP to assess the biogas generation potential for the WWTP (chapter 7). This information, combined with relevant factors including assets, social, economic, and legislative considerations based on stakeholder expectations, can help WWTP operators, urban planners, and policymakers develop energy-efficient and sustainable wastewater treatment systems.

1.2 Aim and research objectives

The thesis primarily aims to develop a sustainability assessment methodology for evaluating the techno-economic feasibility of recovering biogas during WWTP operations, while providing a comprehensive examination of wider resource recovery systems in WWTPs, their benefits, and methods to assess their sustainability.

The research objectives (RO) of this thesis are:

1. Analyse the contributions from energy and resource recovery in WWTPs towards the Sustainable Development Goals (SDGs).

2. Examine the current technology and status of energy recovery from wastewater and sewage sludge in WWTPs.

3. Develop a framework for evaluating the sustainability of energy recovery systems (using biogas as an energy resource) including techno-economic analysis and environmental performance. Demonstrate the framework using an executable tool and a case study approach.

1.3 Research questions

To achieve the research objectives, the thesis poses the following research questions (RQ):

1. How does resource and energy recovery from wastewater treatment contribute to the Sustainable Development Goals (SDGs)?

2. How do we evaluate the feasibility and sustainability of energy recovery from wastewater treatment plants (WWTPs?

3. What is the potential for energy recovery as biogas from wastewater treatment plants (WWTPs)?

The present thesis aims to contribute to the wider adoption and implementation of biogas recovery in WWTPs by providing a deeper understanding of the various aspects of sustainability that must be considered in the implementation of such projects.

1.4 Methodology

This thesis follows an hourglass approach to resource recovery from wastewater treatment plants.

- The thesis begins with a broad review of resource and energy recovery in WWTPs (**chapter 2**) and qualitatively mapping its role in achieving the SDGs (**chapter 3**).
- The focus then narrows to a technological review of energy recovery using biogas as the form of energy recovered (**chapter 4**), and examines the various quantitative methodologies and tools utilized to assess the technical, economic, and environmental sustainability of such energy recovery systems (**chapter 5**).
- A sustainability assessment framework is then developed using sustainability indicators (**chapter 6**) and demonstrated using a case study based on a WWTP in Tbilisi, Georgia (**chapter 7**).
- The thesis then concludes with a broader discussion on knowledge gaps in the resource recovery sector, along with feasible policy instruments and future considerations to improve the sustainability of wastewater treatment sector (**chapter 8**).

The approach is illustrated in Figure 1. The major methods and tools utilised for achieving different objectives of the thesis are described below.

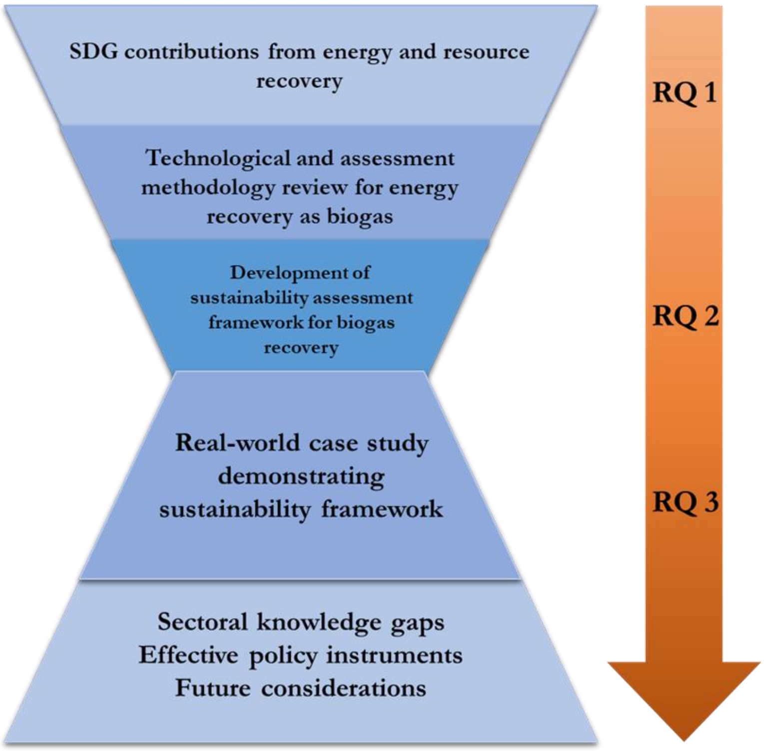

Figure 1 – Methodological structure for thesis

Methods used to address the research questions (RQ):

RQ 1: How does resource and energy recovery from wastewater treatment contribute to the Sustainable Development Goals (SDGs)?

The contributions from resource and energy recovery to the SDGs are derived from a comprehensive review of published research and reports from agencies such as The International Water Association (IWA), World Bank Group, Swedish Gas Association, United Nations Environment Programme (UNEP), United Nations – World Water Assessment Programme (UN-WWAP), and others. A methodology developed by (Hagman and Eklund, 2016) was adapted to map the benefits from resource recovery to the SDGs. The benefits of resource recovery from wastewater treatment were synthesized from the existing literature. The benefits were then classified into 5 different categories –

1. energy recovery;
2. digestate;
3. resource recovery;
4. treatment;
5. concept.

A contribution matrix was then developed to map the benefits from each category to individual SDGs. The methodology and categories are further explained in Chapter 3.

RQ 2: How do we evaluate the feasibility and sustainability of energy recovery from wastewater treatment plants (WWTPs?

The technological review focuses on anaerobic digestion as the primary bio-chemical process for biogas generation in WWTPs. An extensive review of different reactor technologies, process layouts, and research developments is used to synthesize primary information. A comparative assessment is then presented based on the suitability, treatment characteristics, biogas generation potential, and the advantages and disadvantages of each anaerobic digestion technology. Different end-uses of biogas are delineated and technologies to improve biogas output are discussed. Chapter 4 covers the technological review and forms the technological knowledge base for the sustainability assessment in further chapters.

Further, the thesis proceeds with a comprehensive analysis of the technical, economic, and environmental assessment methodologies and tools that have been employed to assess the sustainability of energy and resource recovery projects. Among the different methodologies, their input parameters, results, formulae, assumptions, and standard values were collated and compared to gain an overview of the range of assessment methodologies that are existing today. Based on this observation, a sustainability assessment framework using indicators is developed to indicate the feasibility of recovering and using biogas from WWTPs. The technical, economic, and environmental sustainability of the system is quantified using sustainability indicators that have been widely utilized in existing research. To demonstrate the effectiveness of the developed framework, a case study approach is utilized based on a field visit to a real-world WWTP.

RQ 3: What is the potential for energy recovery as biogas from wastewater treatment plants (WWTPs)?

To demonstrate the potential for biogas recovery and utilize the developed sustainability framework, a case study approach aided by a field study is utilized. The Gardabani WWTP near Tbilisi, Georgia is the site for field study. The field visit provides valuable information about the treatment process and local context but process specific data cannot be obtained due to strict data privacy guidelines at the Georgia Water and Power Company, which owns the Gardabani WWTP. The biogas generation potential in the WWTP is quantified using the developed assessment framework and published data, and the economic and environmental performance of the biogas recovery system is examined. Chapters 5, 6, and 7 cover the comparative assessment of methodologies, development of indicator-based framework, and case study results, respectively.

1.5 Scope and limitations

Resource recovery from wastewater treatment is a multi-disciplinary field of study, ranging from the recovery of energy to recovery of nutrients, bio-fertilizers, minerals, metals, and other valuable resources (Holmgren et al., 2015; IWA, 2018; Kalogo and Monteith, 2012). The thesis thus attempts to provide a holistic view of resource recovery by first qualitatively analysing the benefits and contributions of resource recovery and sustainable wastewater management to the SDGs. Further, to narrow down the focus and scope of the thesis and conduct a comprehensive research in the field of sustainable energy systems, energy recovery through biogas generation in WWTPs is quantitatively analysed. The choice of studying biogas recovery from WWTPs primarily was inspired by discussions with IVL Swedish Environmental Research Institute, Stockholm. IVL has been researching on the biogas potential in developing countries, and wanted to examine the potential for recovering biogas from urban organic substrates such as organic waste and wastewater in the city of Tbilisi, Georgia. To comply with the research requirements, municipal wastewater was chosen as the organic substrate for examination of biogas potential. For the sake of simplicity, the term 'wastewater' in this thesis refers to municipal wastewater and does not consider industrial wastewater as a component of municipal wastewater.

Limitations

To conduct quality research and maintain the focus of the thesis, the scope is limited to analysing energy recovery through biogas generation and assessing the sustainability of biogas recovery systems in WWTPs. As such, an in-depth analysis of all recoverable resources such as nutrients, bio-fertilizers, and other inorganic materials is out of the scope of this project. Further, this research is insufficient to analyse the overall sustainability of WWTPs and examine the various mechanical, chemical, and biological processes that make up the complete wastewater treatment system. An in-depth Life Cycle Analysis (LCA) or Material Flow Analysis (MFA) covering the entire WWTP value chain will be more suitable for those purposes. While there are several other avenues available for resource and energy recovery from wastewater, the focus of this thesis will remain on the recovery of useful biogas during wastewater treatment, and its possible uses inside and outside the WWTP.

The developed sustainability assessment framework is useful for analysing the technical, economic, and environmental performance of biogas recovery from a WWTP. Various data points from real-world observations in existing WWTPs have been utilized to predict the indicators. These may be adjusted accordingly if on-site data is available for the proposed system or if system parameters vary considerably. A list of equations and assumptions used for calculating the indicators is provided in detail in Annexure 1. The resulting indicators from the assessment must be viewed as preliminary results, and any further decision-making must include stakeholder engagement and group discussions to prioritise specific expectations from the biogas recovery system and weigh the indicators accordingly. It is not a technical guideline, but more of a supporting tool for well informed, data-driven decision making. Field specialists and technicians must be involved for further detailed planning and implementation of energy and resource recovery measures in new or existing WWTPs.

A case study approach has been used to demonstrate how the sustainability evaluation can be undertaken using the developed framework for the Gardabani WWTP in Georgia. The evaluation has been conducted using similar data from the national wastewater quality guidelines, as the exact operational data from the studied WWTP could not be obtained due to data privacy guidelines at the Georgia Water and Power Company, which own this WWTP. Data from a similar study for another WWTP in Georgia is used to benchmark the results for the case study.

2 Literature Review

A comprehensive and holistic literature review is the primary data collection tool for this research. Since the field of resource recovery from wastewater treatment plants (WWTPs) is highly inter-disciplinary, an in-depth literature review is useful in synthesizing information on important concepts from different aspects, their benefits and limitations, and to identify sectoral knowledge gaps that are common across research areas (Snyder, 2019). This holistic literature review aims to cover the field of resource recovery from wastewater and sewage sludge, and examines the technologies, assessment and research methodologies, case studies, policies, and research gaps that are established in the current published research. It forms the knowledge base for the research undertaken in the following sub-chapters.

2.1 Wastewater treatment – global status

Water is one of the most important public resource that facilitates the smooth functioning of all sections of society. As human population grows, concerns rise regarding the availability of freshwater and effective wastewater management. In 2017, it was estimated that almost 80% of wastewater globally was released back into the environment without any treatment. The figure was over 95% in some developing countries (United Nations World Water Assessment Programme, 2017). (Mateo-Sagasta et al., 2015) define wastewater as "used water which is discharged from homes, businesses, cities, and agriculture". The sludge generated in WWTPs is referred to as sewage sludge, and is generated when the suspended solids are removed from the wastewater and the soluble organic matter has been converted to bacterial mass, becoming a part of the sludge (Mateo-Sagasta et al., 2015)

Untreated wastewater has detrimental effects on the ecology of water systems, public health, and also pollutes both ground and surface water (dos Santos et al., 2016a; Stazi and Tomei, 2018). The wastewater affects seas and oceans as well, leading to eutrophication due to nutrient discharge into water bodies, and creation of de-oxygenated dead zones. This has affected approximately 245,000 sq. km. of marine ecosystems globally, and impacted food chains, livelihoods, and biodiversity (United Nations World Water Assessment Programme, 2017). It is thus clear that the issue of wastewater management has several cross-linkages with a host of other water-related issues, including the water-energy-food-nutrients nexus (UN-Water, 2015).

Empirical data collected by AQUASTAT and (Sato et al., 2013) indicated that more than 330 km^3/year of municipal wastewater is generated globally. The majorly urban nations of China, United States, Brazil, Russia, India, and Japan generate approximately 167 km^2 of wastewater, accounting for almost 50% of wastewater produced globally. The AQUASTAT data states that almost 60% of the generated municipal wastewater is treated. However, this figure can only be considered a high estimate, as a number of WWTPs, especially in middle and low-income countries are operating below their designed capacities, indicating that actual treatment volumes might be below the reported treatment capacity (Andreoli et al., 2007). There are also variations in the definitions of 'treated wastewater', where some countries only consider secondary and tertiary treated wastewater, while some countries include primary treated wastewater as well. This makes data consolidation and country comparisons difficult and inaccurate. The wastewater characteristics of a few representative countries are shown in Table 1.

Table 1 – Wastewater composition in selected countries (UN-Water, 2015)

Raw wastewater parameters (mg/L)	USA	France	Morocco	Pakistan	Jordan
Biochemical oxygen demand (BOD)	110-400	100-400	45	193-762	152
Chemical oxygen demand (COD)	250-1000	300-1000	200	83-103	386
Suspended solids (SS)	100-350	150-500	160	76-658	-
Total potash and nitrogen	20-85	30-100	29	-	28
Total phosphorus	4-15	1-25	4-5	-	36

The main methods for sludge disposal in developing countries have been and still are landfill, agricultural use and incineration, all incurring very large costs (e.g. $30–70 per wet ton in Australia and €30–100 per wet ton in Europe) (Wang et al., 2017). In developing countries without a well-developed sewerage network, it is a common practice to dump on-site sludge from septic tanks into the existing sewers and wastewater network using dumping trucks. This leads to additional nutrient load on the WWTPs and increases the toxicity of the incoming wastewater (UN-Water, 2015). One of the primary reasons for this is simply the shortage of locally assigned treatment facilities. In low-income countries, sludge and wastewater are generally used informally, owing to the low outreach of wastewater collection and treatment services; while high-income countries usually have a high level of wastewater and sludge treatment - with regulated use, stringent environmental standards, and high awareness of health and environmental benefits (Mateo-Sagasta et al., 2015). The level of treatment is also directly correlated to the countries' income. In low-income countries, only 8% of the generated wastewater was treated, in lower-middle income countries the treatment averaged 28%, while the treatment ratio was closer to 70% in high-income countries (Sato et al., 2013).

Such lack of proper wastewater management has shifted the focus of policymakers and governments to WWTPs and creating an environment where such treatment plants can function viably. Sustainable wastewater management is the need of the hour in developing countries, and even the existing systems in developed countries need to be upgraded to meet the newer stringent environmental performance directives (Iaconi et al., 2017). Further, the focus is shifting on enforcing the circular economy thinking and looking at WWTPs as centers of resource recovery where energy, nutrients, and other organic and inorganic resources can be recovered sustainably (Guest et al., 2009; Mo and Zhang, 2013). Wastewater has long been considered as a health and environmental concern, but there is increasing interest in treating wastewater as a resource and a resource carrier, carrying materials, chemicals, and energy in and out of human society (Van Der Hoek et al., 2016).

Table 2 - Typical properties of untreated and digested sewage sludge (Tchobanoglous et al., 2014)

Item (% dry weight)	Untreated primary sludge		Digested primary sludge	
	Range	Typical	Range	Typical
Total dry solids	2-6	5	6-12	10
Volatile solids	60-80	65	30-60	40
N	1.5-4.0	2.5	1.6-6.0	3
P_2O_5	0.8-2.8	1.6	1.5-4.0	2.5
K_2O	0-1	0.4	0-3	7
pH	5-8	6	6.5-7.5	7

2.2 Resource recovery potential

The role and function of modern WWTPs as just end-of-life treatment and disposal facilities is being re-considered by industry experts, with the focus shifting to looking at WWTPs as avenues to recover valuable resources and become important centers for a bio-based circular economy (Andersson et al., 2016; Rodriguez et al., 2020). There is a need to make these plants more energy efficient, as well as economically viable (Bachmann, 2015). (Maktabifard et al., 2018) note that due to increasing energy costs and decreasing resource availabilities, decision-makers and consumers are taking greater cognizance of the social, environmental, and economic impact of their activities. The paradigm shift in wastewater management dictates that WWTPs must be designed and operated with resource optimization and energy recovery as important objectives. This approach helps facilitate a movement towards energy neutral or energy positive water treatment facilities.

Several concepts have been introduced which look at WWTPs less as an end-of-cycle processing facility, but more as centres where energy, nutrients, fuels can be recovered from urban wastewater resources. (Agudelo-Vera et al., 2012) consider the 'Urban Harvesting Concept' pertaining to urban centres becoming more sustainable by closing urban cycles and harvesting resources from their waste streams, thereby reducing their energy and resource consumptions. Netherlands introduced the concept of 'NEW Factory' which suggests that WWTPs can become factories for recovering 'nutrients, energy, and clean water', and provide a picture of how a sustainable WWTP can operate in the future (Roeleveld et al., 2010). The biorefinery concept envisions WWTPs as factories (refineries) modelled on an oil refinery, where the raw materials (wastewater and sludge) are refined to extract and recover several beneficial products, with wastewater treatment being the primary objective (Amulya et al., 2016; Bertanza et al., 2018). There is also a growing consensus to start looking at wastewater treatment plants as Wastewater Resource Recovery Facilities (WRRF) where resource recovery is a primary function of the facility, along with wastewater treatment (Iaconi et al., 2017; WERF, 2015). The value of recoverable resources varies based on their end uses, with potable water being the most valuable resource that can be recovered during wastewater treatment. A ladder diagram in Figure 2 elucidates the value proposition of different resources based on the cost of recovering the resource.

Wastewater and sludge are important carriers of valuable resources, comprising mainly of water, nitrogen, phosphorous, organic carbon, and the embedded energy potential (see tables 1-3). The embedded minerals are important as agricultural fertilizers, and the organic carbon can be used as a soil revitalizer or to generate clean energy (Andersson et al., 2016; Tyagi and Lo, 2016). Apart from the recovery of water, organic matter, and nutrients, energy recovery provides a high value proposition compared to the costs involved. While several treatment methods require considerable energy during their operation, a net energy gain can be achieved by recovering energy from anaerobic treatment of wastewater and sewage sludge, or valorisation as bio-fuels using thermo-chemical processes (Cao and Pawłowski, 2011). Anaerobic digestion is defined as "a biological process in which a consortium of microorganisms break down complex biodegradable organic matter into methane (50-80%) and carbon dioxide (30-50%) in strict absence of oxygen (anaerobic conditions)" (Lora Grando et al., 2017). The combination of methane and carbon dioxide produced during anaerobic digestion is known as biogas. This helps in reducing the overall energy cost of the WWTPs, while improving the cost-benefit balance for wastewater reuse and recovery. If the country has a carbon credit mechanism, then the emission savings can also provide a substantial revenue stream in the form of saved carbon credits (Hamrick and Gallant, 2018).

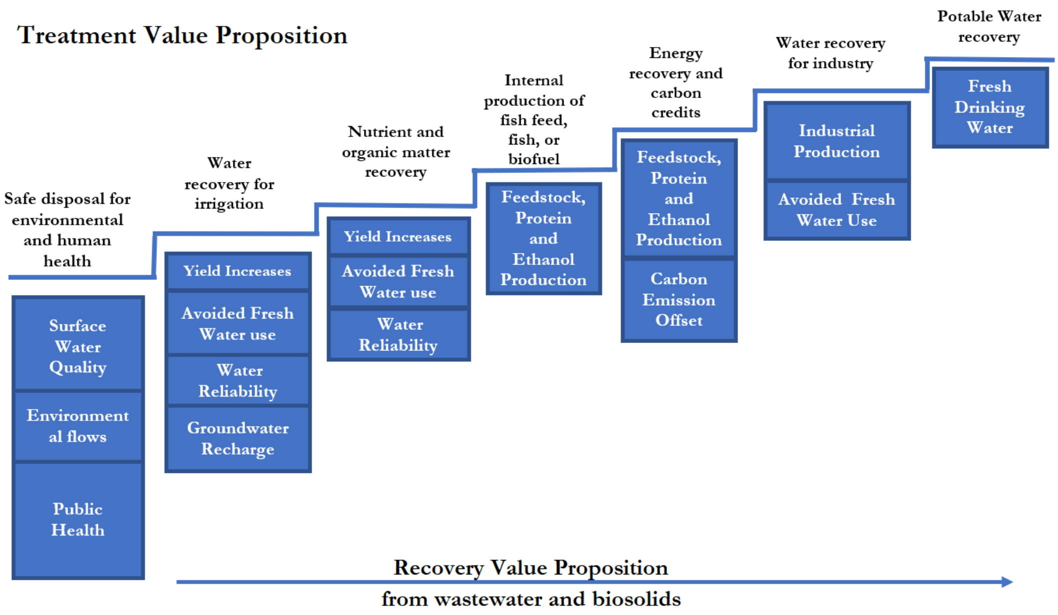

Figure 2 - Ladder diagram showing increasing value of recoverable resources in WWTPs in relation to increasing capital investment and cost recovery potential (Drechsel et al., 2015)

While high levels of wastewater treatment facilitate discharge of cleaner water into seas, lakes, and rivers, it also creates large quantities of sewage sludge, especially in countries with extensive wastewater treatment coverage. Sludge management entails significant efforts and investments, as it can be associated with up to 60%

of the total cost of municipal wastewater treatment (Ramakrishna and Viraraghavan, 2005). Thus, it is imperative for WWTP operators to minimize sludge generation, efficiently treat sludge, and optimize costs related to sludge management (Semblante et al., 2014).

2.2.1 Nutrient recovery as biosolids

The capture and reuse of nutrients from the wastewater treatment process is becoming increasingly common, and the nutrients are made available to the farmers for agricultural applications. However, there is a significant lack of wastewater treatment globally. While only 10-20% of all wastewater generated globally is directed to a treatment facility, around 70-90% wastewater remains completely untreated in low-income and lower middle-income countries (IWA, 2018; United Nations World Water Assessment Programme, 2017).

Sludge has a higher concentration of nutrients and organic matter than wastewater, resulting in higher efficiencies for energy and nutrient recovery. Once the sludge has been properly treated, it can be referred to as biosolids and can be used for agricultural purposes or landscaping (Coyne et al., 2017; Mateo-Sagasta et al., 2015). It contains nutrients like phosphorous and nitrogen which are essential for plants, and has the potential to be a beneficial natural fertilizer. The sludge also has organic carbon, which once stabilized can be used to improve soil structure for plant roots, or converted into energy and fuels through bio-digestion (Mateo-Sagasta et al., 2015). If safe, biosolids can be applied to land to help improve the creation of new soil or improve the chemical and physical qualities of the existing soil. A number of developed countries faced increasing sludge production from their treatment plants and realized that disposal of sewage sludge in water bodies and landfills is an unsustainable and harmful practice. Relevant policies and legislations were thus developed that promote sludge utilization (e.g. by EU and USEPA). This has resulted in increasing use of sewage sludge processing and further applications such as agricultural usage and energy recovery. There is also significant research into the biochemical effects of sludge use for soil generation purposes and developing standards for acceptable quantities for soil use. Developing countries are gradually realizing the value proposition of sludge reuse and are changing their policies and guidelines to address these growing challenges (Harper, 2013)

The beneficial usage of sludge differs from country to country based on the local regulations and development priorities. For countries with low soil nutrition, agricultural use of sludge is preferred, as seen in Spain, where nearly 100% of the biosolids are used in agriculture. In heavily industrialized economies, heavy metals in the sludge might be a cause of concern in soil applications, making energy generation from sludge the more suitable option. This is valid in the Netherlands where almost all the sewage sludge is incinerated for energy recovery. It is thus imperative to separate industrial and domestic wastewater treatment and limit the concentration of harmful chemicals and heavy metals in wastewater streams. On a global level, the utilization of treated sewage sludge continues to grow, albeit on a slower pace. In developing countries such as Turkey, Brazil, Mexico, biosolids are used rather modestly in agricultural applications (<5%), while developed nations such as Japan, Austria, the Netherlands, Germany, are striving to reduce the agricultural use of sludge due to concerns regarding the pollutants present in sludge (UN-HABITAT, 2008)

A representative composition of weak, medium, and strongly loaded wastewater (Table 3) can provide the basis to calculate the approximate ranges of nutrients and organic carbon that can be theoretically recovered from municipal wastewater globally (Tchobanoglous et al., 2014). This theoretical amount disregards the economic or technical limitations and serves to provide an upper bound of the embedded value in the global wastewater streams.

Table 3 - Typical resource composition of raw municipal wastewater of different strengths (Tchobanoglous et al., 2014)

Contaminants/resources	Unit	Concentration		
		Weak	Medium	Strong
Nitrogen (total as N)	mg/L	20	40	85
Phosphorus (Total as P)	mg/L	4	8	15
Total organic carbon (TOC)	mg/L	80	160	290

The related available fertilizer application could be as much as 322 kg N_2/hectare/year and 64 kg Phosphorous/hectare/year, if a medium nutrient concentration in the wastewater is considered (Drechsel et al., 2015). With increasing global population, the demand for agricultural fertilizers is increasing, and nutrient recovery from sludge and wastewater sources can help meet the demand on a local and regional level. The resource recovery implications are particularly interesting around urban areas and cities which are the major sources of wastewater and require an expanding agricultural production to feed the ever-increasing urban population (Andreoli et al., 2007). Such figures, while being highly hypothetical due to various reasons such as the assumption of 100% system efficiency, serve as an important vehicle to raise awareness about looking at wastewater as an asset, and a significant source of valuable nutrients. It is also important to note that these figures only cover the resource recovery potential from urban sources of wastewater, and do not include rural areas.

2.2.2 Phosphorous recovery

Phosphorous recovery is becoming more of a necessity than an option, as it is an essential nutrient that is obtained from finite deposits. It is estimated that the demand for phosphorous will start exceeding the supply by 2035, creating a global challenge for food production and agriculture as there is no substitute available for the nutritional values of phosphorous (Cordell et al., 2011). Wastewater treatment provide a viable opportunity to recover phosphorous from waste streams, with a potential to replace 15% of the global phosphorous demand (Kroiss, 2004). Phosphorous recovery in a WWTP can be implemented in various streams, with recovery possible from untreated influent wastewater directly, from the collected sewage sludge, from the effluent stream received after sludge dewatering, or from incinerating the sludge at the end of treatment (Cordell et al., 2011; Kalavrouziotis, 2017).

Chemical and biological processes have been utilized to recover sludge, with the simplest method to reuse phosphorous being its accumulation in the treated and stabilized sewage sludge and further use as agricultural fertilizer (Andersson et al., 2016; Puyol et al., 2017). Recovery as struvite (magnesium ammonium phosphate) by adding magnesium chloride to wastewater streams with high P content is a common recovery process in large-scale WWTPs, with several full-scale technology demonstrations across the world (Otoo et al., 2015). Countries such as Sweden and Switzerland have mandated phosphorous recovery from wastewater treatment, and are providing the first experiences in what a regulatory framework necessary to unlock the global potential for phosphorous recovery could look like (Andersson et al., 2016; Bachmann, 2015).

Ostara Company is a Canadian enterprise which has successfully implemented a business model for recovering and marketing phosphorous as struvite from wastewater. The recovered crystalline struvite is marketed as branded pellets under the brand-name 'Crystal Green' and are suitable for use as commercial fertilizer. The company shares the revenue from fertilizer sales with the city administration, helping offset the cost of recovery facility (Kalogo and Monteith, 2012; United Nations World Water Assessment Programme, 2017). In an off-site treatment arrangement, a Dutch company – N.V. Slibverwerking Noord-Brabant (SNB) – processes almost 30% of the sewage sludge produced in The Netherlands and extracts phosphorous from the sewage sludge ash. The recovered phosphorous is sold to an international phosphate producer for further processing as fertilizer or pharmaceutical component (Cordell et al., 2011; Schipper and Korving, 2009). The partnership is an example of how industrial collaborations can create effective and sustainable value chains for products recovered from urban waste streams.

2.2.3 Water recovery and reuse as treated wastewater

Water reuse is gaining importance in the global sustainable development agenda because of the following reasons:

- Water scarcity is moving up on the global political agenda, including the Sustainable Development Goals (SDG). Increasing demands for water, due to economic and population growth are placing substantial pressure on the fixed global supply (Bhaduri et al., 2016).

- There are significant environmental gains when treated wastewater reuse is prioritised over existing means of boosting water supply such as building a new dam or transferring water from one basin to the other. Both approaches have significant environmental and economic costs and are unsuitable for sustainable development in the 21st century. Wastewater treatment and water reuse utilizes much less energy compared to water desalination, and its introduction is generally advantageous to the environment and to the people (Tarpani and Azapagic, 2018).

- Governments are starting to understand the 'double value proposition' in water reuse. Without reuse, wastewater treatment has an environmental value, but no financial value. Water, nutrient and energy reuse add new value streams to the proposition (Drechsel et al., 2015).

Sustainable wastewater treatment can help increase the level of wastewater treatment globally and help provide greater volumes of treated wastewater that can reduce freshwater withdrawal for agricultural, sanitation, and industrial purposes and increase water use efficiency (Mo and Zhang, 2013; Rodriguez et al., 2020).

Several water-stressed cities across the world have realized the value of water reuse and are utilizing the wastewater as a resource.

Windhoek, in Namibia, has been a pioneer in upcycling wastewater to potable levels, and is expected to cover up to 60% of the expected water demand by 2020 (United Nations World Water Assessment Programme, 2017). Water reuse is also a valuable tool in cities with unfertile soil conditions. In Lima, Peru, the treated wastewater from Huascar WWTP has enabled the creation of a large urban park in the city centre. The green oasis provides important recreational and social benefits to the residents, while enhancing the soil quality and enabling growth of vegetation in a dry city (di Mario and Drechsel, 2020).

The thermal energy in wastewater can also be utilized for heating buildings. The 2010 Winter Olympic Village in Vancouver, Canada is heated using effluent wastewater from a nearby WWTP, while the Wintower building in Winterthur, Switzerland is heated and cooled using thermal energy extracted from wastewater from a nearby pipeline (United Nations World Water Assessment Programme, 2017).

2.3 Energy recovery potential through biogas

Biogas recovery from wastewater and sewage sludge is a well-established technological practice and can be one of the most valuable resources that can be recovered during wastewater treatment. It has immense potential as a sustainable form of energy that can be utilized for a multitude of useful applications (dos Santos et al., 2016a; Jenicek et al., 2013; Shoener et al., 2014). While biogas production from animal and agricultural waste has been widespread in developing countries, its adoption in WWTPs is still limited (Kalavrouziotis, 2017; Vasco-Correa et al., 2017).

For calculating the global potential, the assumed anaerobic conversion factor of organic carbon to methane of 0.14 m^3 CH_4 per m^3 of wastewater at 20°C is used, with the calorific value of methane being 35.9 MJ/m^3 CH_4 (Lemos Chernicharo, 2007). By utilizing these values, the ~330 km^3 of municipal wastewater produced every year globally can potentially provide 46.2 km^3 CH_4, assuming a medium strength wastewater. The total calorific value (LHV) that can be recovered globally will be 461.1 x 10^9 kWh, which can sufficiently deliver enough electricity for 130 million households, if a household is considered to consume an average of 3500 kWh of electricity (Mateo-Sagasta et al., 2015).

(dos Santos et al., 2016b) in their research specifically present an exhaustive analysis for economic sustainability and energy recovery potential from biogas generation in WWTPs with anaerobic digesters. They evaluate the minimum contributing populations required to achieve economic feasibility needed to install a biogas-derived energy producing wastewater treatment plant in Brazil. A concise methodology for evaluating energy potential and viability is presented, along with a method to analyse avoided GHG emissions.

(Maktabifard et al., 2018) report about a successful implementation of energy recovery in the form of biogas that can be observed in Austria. Two advanced wastewater treatment plants with biological nutrient removal are running with complete energy sufficiency. This is possible as the total electricity consumption is lower than the amount of energy produced by CHP generation from biogas by anaerobic digestion of sludge. Using additional energy recovery measures such as recovery of thermal energy of wastewater, or co-digestion of organic wastes, WWTPs can even achieve 'energy positive' status (Nowak et al., 2015).

Another large-scale WWTP in Philadelphia, USA with a 950,000 m^3/day treatment load faced rising energy prices. The plant decided to increase the utilization of biogas in the CHP engines from 50% to 100% utilization of the generated biogas. The plant was able to a reduce the amount of purchased electricity by a factor of 26, from purchasing 139.7 MWh/day to only 5.3 MWh/day, achieving 54% energy neutrality (WERF, 2015). Significant electricity purchase reductions were also achieved by WWTPs in Melbourne, Australia and Kansas, USA. Major actions to improve energy neutrality included utilizing a higher percentage of the biogas produced for electricity generation in CHP engines, and using co-digestion of organic waste streams. These experiences have been explored in detail by Water Environment Research Foundation in a report on 'Energy Neutrality Leadership' (WERF, 2015).

(Bidart et al., 2014) analysed a successful implementation of energy from biogas production in wastewater treatment plants in Chile. Metrogas, a large gas distribution company in the region has pioneered a project in which the sludge from La Farfana WWTP is utilized in anaerobic digestion. Serving almost 3.6 million inhabitants, the project is one of the largest WWTPs in the world. Almost 24 MM Nm^3/year of biogas is generated, with an average of 63% methane content. The biogas is upgraded by carbon dioxide removal and scrubbing, and then transported to a town gas facility via a 16km pipeline. After catalytic treatment to increase the hydrogen content, the gas is injected into the national gas grid and used for residential consumption purposes.

The Ankara Wastewater Treatment Plant is the biggest WWTP in Turkey. It has been designed for an equivalent population of 4.83 million inhabitants in 2010, with a daily flow rate of 971,000 m^3/day. The plant operates eight anaerobic digesters of 11,250 m^3 capacity each for sludge treatment, producing almost 32,500 m^3/day of methane. This is converted to electricity to generate 70,000 kWh of electric value, satisfying almost 90% of the plant's electricity needs (Berktay and Nas, 2007).

Co-digestion of sewage sludge with organic wastes has been widely considered an efficient strategy to increase the biogas production from anaerobic digesters in WWTPs (Bachmann, 2015). Several successful implementations of large-scale co-digestion in WWTPs are noted by (Shen et al., 2015). An innovative approach from Columbus, USA has been well-documented in the literature regarding co-digestion. The South Columbus Water Resource Facility successfully developed a Columbus Biosolids Flow-Through Thermophilic Treatment ($CBFT^3$) process, which employs a two-staged digester configuration. After receiving the sludge in a thermophilic continuous stirred tank reactor (CSTR), the sludge is treated in two thermophilic plug flow reactors (PFRs) arranged in series configuration, and two parallel mesophilic CSTRs with a 15 day HRT. The plant introduced fat, oils and grease (FOG) co-digestion in 2011, and have since achieved a 25 to 50% increase in biogas generation compared to the digestion of sewage sludge only. Using two 1.75 MW co-generation engines, the plant can meet 40% of its power demands with generated biogas. A net GHG emission reduction of 9600 tonnes of CO_2 equivalents per year is achieved by the combination of the CBFT[3] process, co-digestion of FOG, and co-generation. (Shen et al., 2015) have conducted a comprehensive review of full-scale co-digestion experiences in USA and Europe.

The Csepel WWTP in Budapest, Hungary utilized thermal hydrolysis as a sludge pre-treatment technology to help increase biogas production. Initially, the primary and activated sludges were mixed together, pasteurized, and digested in a thermophilic reactor with a 12 day HRT. The electricity production from this configuration was 78.1 MWh/day, which could offset 49% of the plant's power demands. The plant then incorporated an additional mesophilic digester, and a Exelys™ thermal hydrolysis system, creating a unique DLD configuration – (Digestion-Lysis-Digestion). The implementation of the DLD design has the potential to increase electricity production to 106.2 MWh/day, which would lead to 65% energy self-sufficiency (Gurieff et al., 2012).

Another successful implementation of sewage sludge digestion can be seen at Prague's Central WWTP in Czech Republic. The plant has achieved 100% self-sufficiency for their energy requirements. They were able to boost biogas production from 15 kWh/(PE.year) to 23.5 kWh/PE.year by using several strategies such as 1) improved primary sludge separation; 2) upgrading sludge thickening to lysate-thickening; 3) switching to thermophilic anaerobic digestion; 4) replacing gas turbines with electric power generators and co-generators (Jenicek et al., 2013).

The use of sludge-derived biogas in Sweden has been well-documented and researched. The most common usage of biogas is as vehicle fuel, and the Henriksdal Water Treatment Plant in Stockholm supplies biogas to the public bus transport company, Storstockholm Lanstrafik to run their buses (Lo, Tyagi, 2016). According to the Swedish Biogas Association, 34% of the total biogas production in Sweden (2 TWh in 2016) was from the digestion of sewage sludge, representing the largest source of renewable biogas for the country (Swedish Gas Association, 2018).

3 SDG Linkages to Resource Recovery from Wastewater Management Systems

Figure 3 - UN Sustainable Development Goals

Water and energy are two integral drivers for sustainable development throughout the world (Weitz et al., 2014). While water serves as an important natural resource needed for the smooth functioning of all sectors of the society, clean and renewable energy enables technological and societal progress, and serves as an important resource to improve the quality of life for the society. Further, sustainable consumption of resources and a circular economy minimizing waste are essential to preserve the resource base needed to provide a hospitable environment for future generations Availability of clean water, renewable energy, and efficient resource management are thus prerequisites for sustainable development, encompassing the economic, environmental and social dimensions of development (United Nations World Water Assessment Programme, 2015). Resource recovery from wastewater management systems thus presents a unique opportunity at the water-energy-nutrient nexus to contributes to the progress towards global sustainable development (Mo and Zhang, 2013). In this chapter, the cross-sectional and multidimensional benefits of energy and resource recovery from wastewater treatment systems are synthesized from a comprehensive literature review, and their contribution to the SDGs is mapped using a matrix approach.

The establishment of the Sustainable Development Goals (SDGs) set by the UN has enabled the co-ordination of global efforts towards ensuring the long-term development and well-being of the planet and its people, while providing a set of actionable goals that can ensure that this development is economically, environmentally and socially sustainable. 17 SDGs (see Figure 3) have been established, and range from sustainable consumption of natural resources, strong and innovative industries, to development of an equal and just society with no poverty, good education, peace. Each SDG has various sub-goals, which are supported by several measurable and actionable indicators that facilitate easy monitoring and help track the progress towards the achievement of these goals (IAEG-SDGs, 2018).

3.1 Method used

The Stockholm Resilience Centre has proposed a structural framework of the SDGs where the society and economy are embedded in the biosphere or the natural environment. The structure shows the interdependence and the hierarchy between the various sectors of development, with the natural environment forming the base for our societal and economic activities (Stockholm Resilience Center, 2016). Since wastewater forms a part of the natural resource cycles in the biosphere, sustainable treatment of wastewater and resource recovery while closing nutrient and energy loops has cascading effects on all the levels of development. It is thus important to understand how biogas recovery from wastewater and sludge treatment contributes towards sustainable development goals, and the advantages and effects on the various aspects of social, environmental, and economic sustainability.

Figure 4 - Model for SDGs divided into the three sustainability aspects (Hagman and Eklund, 2016)

In the following section, we divide the goals according to the 3 levels of the SDGs (see Figure 4) and analyse the possible contributions to each goal that can arise from resource recovery from sustainable wastewater treatment. To simplify the analysis, a methodology developed by (Hagman and Eklund, 2016) to study the role of biogas solutions in circular economy and benefits to SDGs is adapted and utilized. The benefits stated in primary scientific literature and organizational reports are collated and analysed for their frequency of mention in scientific literature. When several mentions of a specific benefit have been encountered, the benefits and contribution are assigned into five categories by the author: *energy recovery, nutrient recovery, resource recovery, sustainable treatment, and the concept* (see Figure 5). The 'energy recovery' category consists of the benefits arising from the production and consumption of biogas as a source of renewable energy. 'Nutrient recovery' covers the benefits from using the treated biosolids and its embedded nutrients that are generated as a by-product during wastewater treatment, and the category consists of the benefits arising from the usage of the biosolids in agricultural uses primarily. The 'resource recovery' category covers the benefits arising from recovering and reusing other resources such as minerals, metals, organic feedstocks such as algae and single cell protein. The 'sustainable treatment' category consists of the benefits arising from increased reuse of treated wastewater and increasing levels of wastewater treatment globally, and finally, the 'concept' category aims to include the indirect and more general social and economic benefits arising from resource recovery. Once the benefits have been classified in the 5 categories, a Contribution Matrix is created for each of the 3 levels of SDGs. Each benefit stated in the Contribution Matrix is followed by the relevant citations for easy reference.

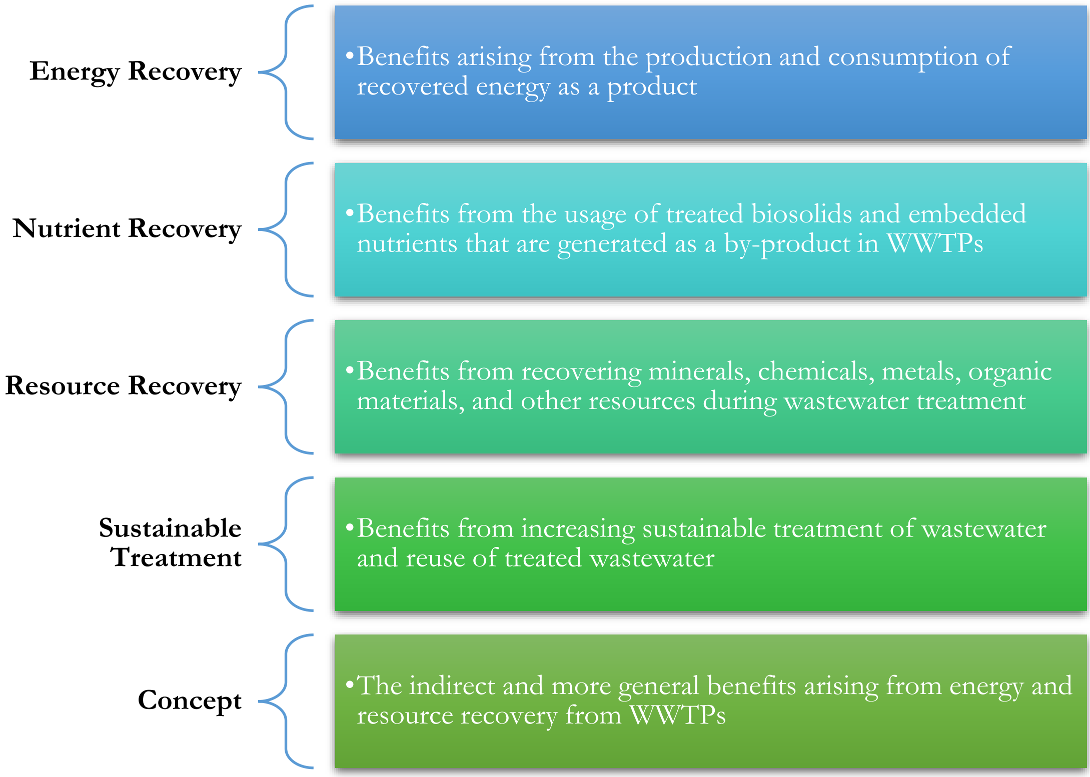

Figure 5 – Components of resource recovery from WWTPs for analysing contribution to SDGs (adapted from Hagman and Eklund, 2016)

The sixth column in the Contribution Matrix describes the various indicators from the Global Indicator Framework for Sustainable Development Goals (IAEG-SDGs, 2018). The indicator study explores the indicators for each goal which can be useful in measuring the impact from each aspect of biogas recovery. While direct measurements of the impact might not be possible with the existing indicators, the positive impact can be captured by developing suitable indicators. It is important to note that an impact from one benefit might contribute to the progress measured by one or more indicators for a particular SDG. The existing indicator framework might also be inadequate in some situations to measure the impact of certain benefits from categories listed in Section 3.2.

3.2 Contributions to biosphere level SDGs

At the biosphere level, the Sustainable Development Goals concern with the preservation of our natural environment and its resources, and to ensure the equal and fair availability of clean water and land resources globally. In line with these goals, resource recovery from wastewater and sludge, and on a larger scale, sustainable wastewater management can contribute to all 4 of the SDGs, i.e. SDG 6, 13, 14 and 15. There are benefits of employing advanced treatment technologies such as anaerobic digestion, membrane filtration, and nutrient removal in wastewater treatment (see chapter 4 for more details) that contribute directly to the clean water and life below water goals (UNEP, 2016; United Nations World Water Assessment Programme, 2017). Further, advanced treatment can help reduce the amount of sludge generated in WWTPs. This reduces the sludge volume sent to landfills for end disposal, and methane capture reduces leakage into the atmosphere, reducing the greenhouse gas effects of methane and adding to the climate action goal – SDG 13 (Demirbas et al., 2016; Levlin and Hultman, 1998). Research also shows that nutrient removal during wastewater treatment helps in reducing eutrophication in downstream water bodies, and the wider adoption and spread of this technology in developing countries will greatly enhance quality of water bodies receiving treated wastewater (Garrido-Baserba et al., 2016; IWA, 2018). The availability of treated wastewater for agricultural irrigation also reduces the need for freshwater withdrawals and relieves pressure on already stressed water resources (Mateo-Sagasta et al., 2015; Mo and Zhang, 2013). In progress towards the life on land goal – SDG 15, there are definite benefits of replacing traditional mineral fertilizers with organic biosolids generated as a by-product stabilizing and treating sludge generated in WWTPs (UN-HABITAT, 2008). Biosolids application improves soil quality by providing an organic and nutrient rich medium. Resource recovery from wastewater can also prove to be a viable source of recovering phosphorous for fertilizers and other purposes, reducing the amount of mineral mining needed to obtain these resources (Andersson et al., 2016; Drechsel et al., 2015). Thus, we can see strong direct correlations between the biosphere level SDGs and the benefits of resource recovery from wastewater and sludge and integrated water resource management. The contribution matrix for biosphere goals is shown in Table 4.

3.3 Contributions to society level SDGs

At the society level, the SDGs relate to the sustainable growth of developing and least-developed countries, and concern with achieving universally acceptable levels of education (SDG 4), healthcare (SDG 3), justice (SDG 16), and national security and peace (see Figure 4). The goals are diversified at the society level, and it becomes difficult to draw direct synergies between the benefits and the SDGs. However, several indirect and cascading benefits can be noticed. The goals no poverty, zero hunger, good health, quality education, and gender equality are concerned with creating a peaceful society where sustainable development is benefitting everyone equally. Wastewater treatment and energy recovery has some direct and indirect benefits that can contribute towards these goals.

Table 4 - Contribution of wastewater treatment components towards biosphere level SDGs. (Compiled by author)

Biosphere SDG	Energy Recovery	Nutrient Recovery	Resource Recovery	Sustainable Treatment	Concept	Indicator
6 CLEAN WATER AND SANITATION		Biosolids application in agriculture replaces harmful fertilizers that enter water basin systems (Kroiss, 2004; UN-HABITAT, 2008)	-Improve availability of sustainable sanitation systems -Increased amount of treated WW available for reuse, reducing freshwater withdrawal (Laitinen et al., 2017; United Nations World Water Assessment Programme, 2017)	Effluent water quality is aided by reducing sludge and pathogens during advanced treatment. -Can provide a viable source of potable or non-potable water through re-use of treated WW (United Nations World Water Assessment Programme, 2017)	- Widespread adoption of sustainable wastewater resource recovery will aid in increasing wastewater treatment globally - Opportunity for increased WWT in developing countries (IWA, 2018; Laitinen et al., 2017)	Energy, nutrient & resource recovery: 6.3.1; 6.3.2; 6.4.1; 6.5.1; Sustainable treatment & Concept: 6.3.1; 6.3.2; 6.4.1; 6.5.1; 6.5.2; 6.a.1;
13 CLIMATE ACTION	- Reduced CO_2 and NO_x emissions (Silvestre et al., 2015; United Nations World Water Assessment Programme, 2017) - Sustainable energy supply - Replaces fossil fuels (Shen et al., 2015; UN-HABITAT, 2008)	- Reduced use of energy intensive mineral fertilizers - Enables organic farming (Iaconi et al., 2017; Swedish Gas Association, 2018)	-Help reduce emissions by recovering resources that would be produced in traditional industries (Holmgren et al., 2015)	Reduces GHG emissions from the wastewater treatment sector - Reduces eutrophication of water bodies (IWA, 2018; Venkatesh and Elmi, 2013)	Innovation and widespread recovery will contribute to emissions reduction from various sectors - Moving towards a circular economy (Iaconi et al., 2017; Kalogo and Monteith, 2012; Kiselev et al., 2019)	Energy: 13.2.1; 13.2.2; Nutrient & Resource: 13.2.1; 13.2.2; Treatment: 13.2.1; 13.2.2 Concept: 13.2.1; 13.2.2
14 LIFE BELOW WATER		- Prevents release of harmful substances into water sources - Biosolids are used instead of being disposed (Andersson et al., 2016; Kalavrouziotis, 2017; Kiselev et al., 2019)		-Increased pathogen removal - Reduced biological loading in wastewater prevents eutrophication (Andersson et al., 2016; Stazi and Tomei, 2018)	Widespread adoption of anaerobic digestion will aid in improving water treatment globally - Improved economics - promotes water treatment in developing countries (Laitinen et al., 2017; Shoener et al., 2014)	Nutrient: 14.1.1; 14.3.1 Treatment: 14.1.1; 14.2.1; 14.3.1 Concept: 14.1.1; 14.2.1; 14.3.1;
15 LIFE ON LAND	- Replaces fossil fuels whose extraction cause land degradation (Jain, 2019)	- Improves soil quality by providing organic matter - Prevents soil degradation by excessive fertilizers & pesticides - Helps avoid landfilling of sludge (Jain, 2019; UN-HABITAT, 2008)	Reduced -land degradation by meeting some demand for traditionally mined resources such as phosphorous and other metals (Holmgren et al., 2015; Raheem et al., 2018)	-More reused water available for irrigation and agriculture -Sludge disposal in landfills avoided (Puyol et al., 2017; Sato et al., 2013; Semblante et al., 2014; Tyagi and Lo, 2016; UN-HABITAT, 2008)	-Can help provide water, nutrients, and bio-fertilizer to improve land quality -Increased resource recovery reduces demand from land-based resources (di Mario and Drechsel, 2020; Kroiss, 2004; Oladejo et al., 2019)	Energy: 15.2.1; 15.3.1 Nutrient & Resource: 15.2.1; 15.3.1 Treatment: 15.2.1 Concept: 15.2.1

The energy recovered in wastewater treatment plants is usually consumed for the plant's energy needs (SDG 7). However, if repurposed and transported outside the plant, recovered energy resources can be to provide energy access to communities, especially in developing countries. Biogas is a highly versatile fuel, and can serve as a cooking fuel replacing firewood and kerosene, improving the access to clean energy for energy-stressed communities, improving the quality of life and providing economic opportunities as well (Tilley et al., 2014; Venkatesh and Elmi, 2013). As a replacement cooking fuel, it has several benefits in improving the indoor air quality due to cleaner combustion and can also help women and children save considerable time that is used for collecting firewood. Biogas usage also reduces dependence on fossil fuels, and usage in any application leads to reduction in emissions of carbon dioxide, and other harmful gases.

The no poverty goal (SDG 1) development is indirectly supported by energy and resource recovery, availability of organic biosolids that improves the agricultural yield for farmers, and growth of widespread wastewater treatment facilities creating employment (Andersson et al., 2016; Hagman and Eklund, 2016). The zero-hunger goal (SDG2) is similarly influenced by water reuse and biosolids, as the digestate and treated wastewater indirectly aid in boosting urban agricultural output (Hernández-Sancho et al., 2010; Mateo-Sagasta et al., 2015). The progress towards the good health goal (SDG 3) is contributed by all 5 aspects stated in Figure 5 in similarly cascading manners. Usage of recovered energy instead of fossil fuels prevents the emission of greenhouse gases (Molinos-Senante et al., 2014b), the organic biosolids promote organic farming and help replace harmful mineral fertilizers and pesticides (Otoo et al., 2015), better wastewater treatment reduces pathogens in the effluent water, and improves the water quality downstream (IWA, 2018). Looking at further goals, development and adoption of energy and resource recovery from wastewater treatment contribute greatly towards the clean and affordable energy goals (SDG 7), both directly and indirectly. Biogas serves an important role in reducing dependence on fossil fuel consumption in WWTPs and in other avenues (dos Santos et al., 2016b), while resource recovery can help reduce energy demand in industrial processes by reducing demand from traditional suppliers (Cordell et al., 2011). In a more indirect contribution to SDG 7, the availability of good quality organic biosolids from WWTPs help replace energy intensive mineral fertilizers. All of the above direct and cascading benefits ultimately correlate with the sustainable cities and communities goals (SDG 11), as usage of recovered energy, agricultural application of organic biosolids, sustainable and integrated water resource management with resource recovery, and the overall impact of the wide deployment of sustainable WWTPs in rural and urban areas will ultimately help in creating sustainable and resilient communities (Agudelo-Vera et al., 2012; Weitz et al., 2014).

The final goal on the social level, 'Peace, Justice, and Strong Institutions', is supported by aspects such as energy independence, better transnational water relations, and development possibilities in rural and semi-urban area. Many conflicts today are due to resource scarcity, and biogas, biosolids, and wastewater treatment solutions can help alleviate these scarcities by providing solutions to energy, food, and water challenges. Table 5 depicts the contribution matrix for social SDGs.

Table 5 - Contribution of wastewater treatment components towards society level SDGs. (Compiled by author)

Society SDG	Energy Recovery	Nutrient Recovery	Resource Recovery	Sustainable Treatment	Concept	Indicator
1 NO POVERTY	- Biogas can be supplied to poor households as cheap energy, replacing wood and other biomass (Jain, 2019; Weiland, 2010)	-Increased agricultural employment opportunities (Hagman and Eklund, 2016)	-Create employment through new opportunities for agriculture, resource supply chains, and employment in WRRFs. (Holmgren et al., 2015; United Nations World Water Assessment Programme, 2017)	- Employment opportunities as sustainable WWTPs proliferate -Increase access to basic sanitation services (Andersson et al., 2016; UN-HABITAT, 2008)	-Sustainable WWTPs and resource recovery value chains will generate employment opportunities (Andersson et al., 2016)	Energy: 1.4.1; 1.a.1 Nutrient & Recovery: 1.2.1 Treatment & Concept: 1.4.1
2 ZERO HUNGER		-Bio fertilizers can help bring more land under productive agriculture use; increased food output - Improved soil fertility due to organic fertilizers (Andersson et al., 2016)	-WW reuse for agriculture can help increase land under irrigation, increase productivity, and improve sustainability and resilience of agricultural systems.-Recovered bio-fertilizers and mineral can provide an organic form of nutrition for agriculture. (Laitinen et al., 2017; UN-Water, 2015)	- Improved water treatment delivers more clean water for agricultural purposes, improving yields (Drechsel et al., 2010)		Nutrient: 2.3.1; 2.3.2; 2.4.1 Resource & Treatment: 2.3.1; 2.4.1 Concept: 2.1.2; 2.3.1; 2.4.1
3 GOOD HEALTH AND WELL-BEING	- Reduction in CO_2, NO_x, and CH_4 emissions by using biogas instead of fossil fuels help reduce air pollution (dos Santos et al., 2016b; Shen et al., 2015)	-Improved nutrition can be achieved by increasing agricultural productivity (Andersson et al., 2016)		Treatment of effluent water reduces occurrence of water-borne diseases (United Nations World Water Assessment Programme, 2017)	- Resource recovery from wastewater reduces air, water, and soil pollution, creating a cleaner natural environment (Jain, 2019; Kalavrouziotis, 2017; Rodriguez et al., 2020; Tyagi and Lo, 2016)	Energy: 3.9.1; 3.9.3; Nutrient: 3.9.3 Treatment: 3.9.2; 3.9.3 Concept: 3.9.1; 3.9.2; 3.9.3
4 QUALITY EDUCATION						

Table 5 (contd.) - Contribution of wastewater treatment components towards society level SDGs (compiled by author)

Society SDG	Energy Recovery	Nutrient Recovery	Resource Recovery	Sustainable Treatment	Concept	Indicator
5 GENDER EQUALITY						
7 AFFORDABLE AND CLEAN ENERGY	- Source of clean sustainable energy - Reduces fossil fuel demand in WWTPs and other applications. - Improves energy efficiency of water treatment (Silvestre et al., 2015)	- Reduces reliance on energy-intensive extraction of mineral fertilizers (Andersson et al., 2016; Hagman and Eklund, 2016)		- Energy efficient water treatment achieved by recovering energy and nutrients (Gu et al., 2017b; Jenicek et al., 2013; Shoener et al., 2014)	- Increased research and market interest will improve process efficiencies - New WWTs in developing nations can be designed to provide substantial bio-energy (Gu et al., 2017a; Gurung et al., 2018; UN-HABITAT, 2008)	Energy: 7.1.2; 7.2.1; 7.3.1; Nutrient: 7.3.1; Treatment: 7.3.1; Concept: 7.1.2; 7.2.1; 7.3.1; 7.a.1; 7.b.1
11 SUSTAINABLE CITIES AND COMMUNITIES	- Sustainable source of energy - Can be used in multiple sectors in the society - Encourages circular economy - Improves energy independence (Hagman and Eklund, 2016; Venkatesh and Elmi, 2013)	- Promotes organic farming and better agricultural practices - Provides a quality fertilizer for increased use in urban agriculture - Helps maintain soil quality for future generations (Andersson et al., 2016; Iaconi et al., 2017; Jain, 2019; Kroiss, 2004)	-Reduce environmental impact of cities by reducing demand for freshwater withdrawal and improved waste management (Holmgren et al., 2015)	- Better water treatment, reuse and resource recovery - Availability of treated water for urban agriculture - Improved water resource management (di Mario and Drechsel, 2020; Rodriguez et al., 2020; World Bank, 2019)	- Increased sanitation and water treatment in urban settlements - Availability of a sustainable source of energy - Decreases need for freshwater dependence (Kiselev et al., 2019; Rosemarin et al., 2008; Tilley et al., 2014; UN-Water, 2015)	Nutrient: 11.3.1; 11.a.1 Resource & Treatment: 11.6.1; 11.a.1; Concept: 11.3.1; 11.6.1; 11.6.2; 11.a.1; 11.b.2;
16 PEACE, JUSTICE AND STRONG INSTITUTIONS						

Table 6 – Contribution of wastewater treatment components towards economic level SDGs (compiled by author)

SDG	Energy Recovery	Nutrient Recovery	Resource Recovery	Sustainable Treatment	Concept	Indicator
8 DECENT WORK AND ECONOMIC GROWTH		- Increased agricultural output - Cheaper fertilizer for farmers - Added revenue stream for WWTPs (Mateo-Sagasta et al., 2015; Mo and Zhang, 2013; Rodriguez et al., 2020)	-P recovery can reduce dependence on industrial production of P, reducing need for extracting mineral P. -Reduced fertilizer use in agriculture. (Laitinen et al., 2017; UN-Water, 2015)	-Resource recovery promotes circular economy -Reduces consumption of freshwater, and increases energy and infrastructure efficiency of wastewater treatment (Andersson et al., 2016; Kiselev et al., 2019)	- Decouples economic growth from environmental degradation - New jobs created as WWTPs become economically feasible (Hagman and Eklund, 2016; IWA, 2018; United Nations World Water Assessment Programme, 2017)	Nutrient & resource: 8.3.1; 8.4.1; 8.4.2; Treatment: 8.4.1; 8.4.2; Concept: 8.3.1.; 8.4.1; 8.4.2;
9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	- Energy efficient WW treatment using renewable energy (Gu et al., 2017a; Jenicek et al., 2013; Shoener et al., 2014)	- Helps upgrade agricultural industry to sustainable practices with increased resource efficiency (Andersson et al., 2016)	-Mineral and resource recovery can reduce the demand from unsustainable industrial processes -Provide employment for skilled labour in resource recovery facilities -Bioplastics recovery can reduce dependence on petroleum plastic. (Holmgren et al., 2015; Raheem et al., 2018)	- Efficient reuse of treated WW in various sectors practices - Innovation in terms of creating biorefineries (Amulya et al., 2016; di Mario and Drechsel, 2020; Holmgren et al., 2015)	- Development of sustainable wastewater treatment infrastructure - Innovation in resource recovery and efficiency - Promotes circular economy and sustainable consumption (Kiselev et al., 2019)	Energy: 9.4.1; Nutrient: 9.2.1; 9.4.1 Resource: 9.2.2; 9.4.1 Treatment: 9.4.1 Concept: 9.2.1; 9.4.1; 9.5.1; 9.a.1;
10 REDUCED INEQUALITIES						
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	- Usage of biogas as a sustainable energy source - Promotes closing the energy loop - Reduces wastage of resources (Jain, 2019; Kiselev et al., 2019; Mo and Zhang, 2013)	- Organic fertilizers maintain soil quality - Replaces usage of harmful fertilizers (Andersson et al., 2016; Rosemarin et al., 2008)	-Enhance resource efficiency and sustainable production -Improve lifecycle management of chemicals and minerals. (Holmgren et al., 2015)	- Improves water reuse and resource recovery - Reduces wastage of valuable water (di Mario and Drechsel, 2020; United Nations World Water Assessment Programme, 2017; Van Der Hoek et al., 2016)	- Promotes responsible consumption - Strengthens circular economy' - Prevents air, land, water pollution (Drechsel et al., 2015; Puyol et al., 2017; Raheem et al., 2018)	Biogas: 12.2.1; 12.2.2; Digestate: 12.4.1; 12.5.1 Treatment: 12.4.1; 12.5.1 Concept: 12.6.1; 12.a.1;

3.4 Contributions to economic level SDGs

The contribution matrix in Table 6 shows the benefits to economic SDGs. These goals consist of ensuring decent work and economic growth (SDG 8), creating innovative industries and resilient infrastructure (SDG 9), reducing economic inequalities (SDG 10), and ensuring responsible production and consumption practices (SDG 12). Since wastewater treatment and energy production are important industrial processes and part of the urban economy, it is important to understand how sustainable wastewater management with biogas recovery can help achieve the objectives of the economic level SDGs, and map their contributions and benefits towards each goal.

For the decent work and economic growth goal, we can see several indirect benefits that can contribute towards economic growth. The availability of cheap and good quality organic digestate is important for farmers. By using the organic fertilizer, they can improve the quality and quantity of their produce, reduce dependence on increasingly expensive and harmful fertilizers and pesticides, and utilize the economic savings to grow their income in a sustainable manner, while improving their own working conditions by preventing exposure to harmful effects of pesticides (Mateo-Sagasta et al., 2015; Rodriguez et al., 2020). The organic biosolids can also be an important revenue stream for WWTPs if sold to the market, thereby improving the cost-benefits ratio for the producers. From the water treatment perspective, it is imperative that the growing urban economy is based on responsible use of natural resources. Thus, as urban demand for water grows, it will become increasingly important that a fair share of that demand is recovered from wastewater treatment and water reuse (IWA, 2018; Kiselev et al., 2019). The widespread proliferation of WWTPs in all urban areas will create new industries, new jobs, and economic growth by providing an essential utility service with tangible environmental benefits (United Nations World Water Assessment Programme, 2017). The bio-refineries concept is especially interesting in this context, as the WWTPs of the future will take on more roles as producers of energy, materials, resources, and not just centres of water treatment (Amulya et al., 2016). The reuse and resource recovery potential is thus a major component of promoting circular economy.

Discussion

It is apparent from the contribution matrix approach that resource recovery and sustainable wastewater treatment have multi-dimensional benefits that can encompass several dimensions of sustainability. The interlinkages are important to note as the social value proposition is usually not captured in conventional economic value analyses. While the existing examination of scientific literature revealed several cross-linking benefits, it is still inadequate to cover certain social aspects of benefits, such as contribution to education and gender equality goals. This is because the focus of this research is from a resource and energy efficiency point of view. These benefits may be clearer in scientific research from sociological and development-based perspectives. The blank matrix spaces signify that no clear benefits for that component could be discovered in the covered literature review.

As such, the matrix includes only the benefits that have been directly referenced in literature. However, there are further cross-sectional and interlinked advantages to achieving a particular goal, that can contribute to progress towards other goals as well. For example, reducing the occurrence of water-borne diseases through increased sanitation and treatment of wastewater can help children attend school for longer, help workers avoid sick days, and thus contribute to goal 4 as well (Andersson et al., 2016). Such linkages need further empirical study to be well-established in literature, and thus have not been included in the current analysis.

It is also important to note the contextual relationship of these benefits with local factors such as demographics, economic conditions, geography, institutional and policy framework, etc. The benefits accrued and suitable technological options will depend on these factors. The benefits accrued due to certain resource recovery options in one context might have detrimental effects on sustainability in another. Local considerations and on-ground analysis are thus important to understand the true nature of benefits that can be realised by resource recovery and sustainable wastewater treatment.

3.5 Guiding principles for sustainable resource recovery systems

(Guest et al., 2009) proposed guiding principles for design of sustainable resource recovery systems (RRS), as shown in Table 7. The authors proposed a set of guiding principles for selecting and implementing resource recovery systems that will fall in line with sustainability principles and will not be overlooking any aspect of social, environmental, and economic sustainability. While the guiding principles are designed such that they can be used as a checklist for evaluating any RRS applied to water, assessing biogas recovery systems along these guidelines can provide an important underlying framework of sustainability considerations that can be easily cross-referenced during the whole design and planning phase. The characteristics of a RRS that are described in the guiding principles are an idealized collection of sustainability goals, and any singular project will certainly be unable to achieve them all simultaneously. They are instead meant to guide stakeholder decision making and planning process, as they design a resource recovery system that will be well-suited for their local conditions and requirements, and will be able to achieve the sustainability goals that are relevant to the project-specific applications. The thesis follows these guiding principles in the design of sustainability assessment indicators, keeping in mind the various environmental, functional, and economic characteristics described by Guest et al.

Table 7 - Proposed guiding principles for Sustainable resource recovery systems applied to water. Adapted from (Guest et al., 2009)

Category	Characteristics of a Sustainable RRS
Environmental	Will not generate waste Will be net energy positive or neutral Will not deplete water resources nor alter natural hydrological processes Will achieve responsible nutrient management and contribute to soil fertility Will not consume non-renewable or non-recoverable resources Will nor contribute to global warming
Ecological	Will not diminish ecosystem health Will not reduce biodiversity nor threaten individual species
Economic	Will have lifecycle costs that are affordable to all stakeholders Will contribute to the economic development of the municipality and beyond
Social	Will provide access to safe drinking water and appropriate sanitation for all will protect public health Will be understood and accepted by all stakeholders Will not disproportionately impact a segment of the population Will apportion costs equitably and in proportion to benefits received
Functional	Will be flexible and adaptable Will be reliable and resilient Will be manageable and safe for operational staff

4 Technologies for Energy Recovery Through Biogas

In this section, we will look at some of the preferred technologies used for anaerobic digestion of domestic wastewater, as well as of sewage sludge. While there are several studies dealing with specific technologies such as UASB reactors (Chernicharo et al., 2015), there is still a lack of comprehensive reviews of high-rate anaerobic digestion processes. The goal of this section is to analyse the available high-rate systems in the market today, and highlight the benefits and drawbacks of each configuration. High-rate anaerobic digestion processes employ techniques to retain the anaerobic bacterial mass in the reactor, which enables these reactors to have much lower hydraulic retention times (HRT), while maintaining a significantly higher solids retention time (SRT) (De Mes et al., 2003). High-rate systems are ideal for wastewater treatment due to the large influent volume of wastewater.

Anaerobic digestion (AD) is an important technology for wastewater treatment and sewage sludge stabilization. With proven large-scale implementations and continued research and development, it is emerging as a prime treatment technology that is well in-line with the concepts of sustainable wastewater management and can also contribute to several of the Sustainable Development Goals. AD gives the opportunity to recover energy in the form of biogas, and valuable organic resource in the form of stabilized sludge which can serve well as a soil conditioner. AD also helps improve the quality of effluent stream by removing pathogens and decreasing the further release of methane into the atmosphere.

Through the generation and recovery of biogas, AD plants present a tangible opportunity for WWTPs to generate heat and electricity and improve their energy independence. They can further reduce costs and increase the overall environmental performance by shifting from fossil fuels to generation of renewable energy. Several technologies have been developed since the first anaerobic digestion plants were operated in the late 19th century (Kalogo and Monteith, 2012). It was initially thought that AD is suitable for only high-strength wastewater (refer Table 3 for different wastewater strengths) such as industrial effluents, and at moderate temperature conditions of 20-25°C. Consequently, the first anaerobic reactors were employed in tropical countries to treat mainly industrial wastewaters. However, further developments in efficiency and process design in the 1980s suggested that anaerobic digestion processes in correct configurations could also be effectively used to treat low-strength wastewaters at low temperatures (Stazi and Tomei, 2018). AD nowadays is usually carried out in high-rate anaerobic reactors, which are bioreactors with mixing and heating apparatus, and the necessary monitoring equipment to monitor and control the required process conditions. The biogas production status in various countries is tabulated in Table 8.

Anaerobic digestion can be used as a treatment for wastewater, or sludge, or for both treatment lines in a WWTP. (Mccarty et al., 2011) compared the energy recovery potential in a complete anaerobic treatment setup and a conventional activated sludge system with anaerobic digestion of the sludge, and noted that the methane recovery doubled by implementing anaerobic digestion in both the treatment lines. The recovered energy was more than enough to meet the plant's energy needs. There is also a significant reduction in the amount of digested sludge produced compared to aerobic treatment, thereby accruing another significant energy and cost benefit. Thus, there is a scope for energy recovery from wastewater as well as sludge.

(Tyagi and Lo, 2016) review the various technologies that are available today to recover energy and other resources, specifically from sludge. The paper contains a comprehensive review of various full-scale projects that are currently employing these technologies to recover energy and resources, and delineate some of the industrial best practices. Utilizing the energy from wastewater and sludge can help in achieving energy security, lower greenhouse gas emissions, and reduce dependence on fossil fuels for energy needs. While assessing the feasibility of a particular pre-treatment method, it is important to consider extra biogas production, total amount of sludge produced, total energy balance, and overall costs have to be accounted for and analysed (Rulkens, 2008). The authors' research indicates that electricity costs are almost 80% of the total operational cost of the treatment plant, and energy generated from recovered methane can cover about half of this cost (Tyagi and Lo, 2016).

Table 8 - Biogas production from wastewater in various countries. Adapted from (Bachmann, 2015)

Type of energy utilized	Country	Total biogas production (including co-digestion of other waste)	Biogas production only from sewage sludge in WWTPs)	
		GWh/year	GWh/Year	% of total production
Energy generated as gross gas production	Denmark	1280	250	21
	Norway	500	164	33
	South Korea	2578	969	38
	Sweden	1686	672	40
	Switzerland	1129	550	49
	Netherlands	3631	711	20
Energy generated as electricity, heat, fuel or flared	Finland	567	126	22
	Germany	41550	3050	7
Electricity generation only	Austria	570	n.d.	n.d.
	Brazil	613	42	7
	France	1273	97	8
	United Kingdom	6637	761	11

When it comes to designing an anaerobic digestion process for treating sludge in municipal sewage treatment plants, the study by (Tezel et al., 2011) provides an in-depth understanding on the microbiological and process considerations The authors briefly discuss sludge characterization, and provide a technically sound encyclopaedia of anaerobic digestion, including the microbial processes involved, process control parameters, and the benefits of anaerobic digestion as a method for sludge stabilization. Various disposal methods and reuse applications are discussed and the regulatory framework controlling these disposal methods are touched upon.

(Tezel et al., 2011) mention that untreated sludge that is disposed in landfills releases methane, which is a major greenhouse gas when it escapes into the atmosphere. Implementing aerobic digestion is an effective method to capture methane during wastewater and sludge treatment, and using the captured methane to produce electricity for the wastewater treatment plant reduces the consumption of fossil fuels, thereby cutting down on CO_2 emissions. Methane generation from sewage sludge is thus a feasible source of renewable energy.

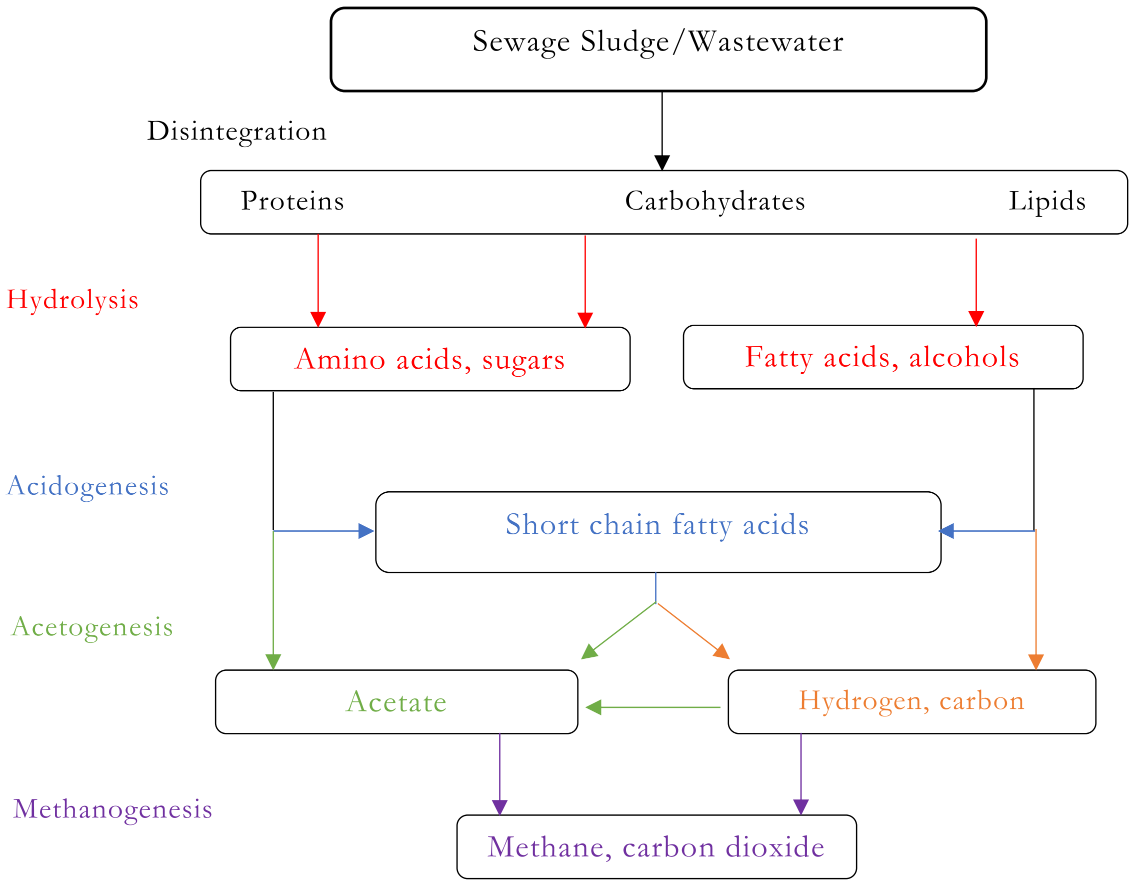

Figure 6 - Anaerobic digestion microbial process stages Adapted from (Tezel et al., 2011)

4.1 Anaerobic digestion technologies for wastewater treatment

1. Anaerobic Filter (AF) – The anaerobic filter design was first conceptualized by Young and McCarty in 1969, and has since been used widely for both low and high-strength wastewaters (Young and McCarty, 1969). The reactor consists of one or several filter beds that are stacked vertically and contain anaerobic biomass that is attached to inert media, facilitating a large exchange area and longer retention of biomass. There can be one or more filtration chambers attached in series to increase the effectiveness of the process. The influent wastewater is fed from the bottom in an upflow configuration, flowing through the filter medium and allowing contact between the microorganisms and the wastewater, which leads to the organic matter being degraded by the active biomass attached to the medium (Stazi and Tomei, 2018; Tilley et al., 2014)

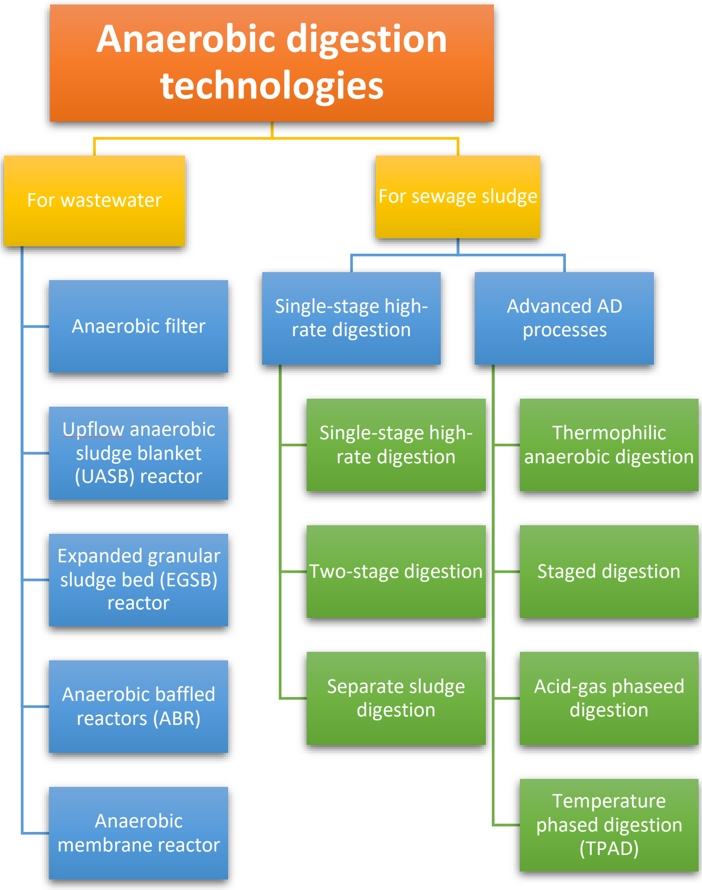

Figure 7 – Anaerobic digestion technologies available for wastewater and sludge treatment

The anaerobic filter (AF) is a highly adaptable system and can be used from household level to town level applications, provided that the system is sized correctly. The AF systems can achieve up to 90% suspended solids and BOD removal, although the typical removal is between 50-75% (Tilley et al., 2014). Typical hydraulic retention times range from 1 to 3 days, and COD loading can be between 5 to 20 kg/m^3.day (Tchobanoglous et al., 2014). The AF is getting recognition nowadays as an effective alternative solution for direct anaerobic digestion of low-strength wastewater without heating requirements. It is especially suitable for small-scale decentralized treatment plants in areas with moderate climate.

Advantages of AF include (Manariotis and Grigoropoulos, 2006; Stazi and Tomei, 2018; Tilley et al., 2014):

1. High suspended solids (SS) removal efficiency, eliminating the need for solid separation in the effluent.

2. Low HRT compared to other high-rate anaerobic reactors.

3. Less sensitivity to shock loads.

4. Quick recovery of biological activity when restarted after interruption.

5. Low capital, operation, and maintenance costs.

6. Low space requirements as it can be built underground.

2. Upflow Anaerobic Sludge Blanket (UASB) Reactor - The UASB reactor is the most widely used anaerobic reactor technology currently. It was developed in the 1970s by Lettinga and his associates, and has proven to be one of the most successful anaerobic treatment technologies so far. UASB reactors are well suited for large-scale applications, being extensively used as primary treatment in WWTPs serving one million and higher population equivalent loads (Chernicharo et al., 2015). It is built as a single tank system, with the influent being fed in upflow mode. Two main zones exist within the reactor: a sludge blanket zone where the organic matter degradation occurs aided by the presence of micro-organisms, and the sedimentation zone where the large particles in sludge settle down. The anaerobic micro-organisms form small agglomerates that stay at the bottom of the tank due to their weight. This allows the active anaerobic sludge to be easily retained in the reactor without the need for packing medium or filters for attachment of the organisms. The upflow velocity of the influent provides efficient mixing and contact between the organic matter in the sludge and the highly active micro-organisms. The methane and carbon dioxide developed from organic matter degradation rise in the reactor, and a gas-solid-liquid separator at the top of the tank prevents the biological matter from being washed out along with the gas and treated effluent. The effluent is removed at a point higher than the phase separator and the biogas can be recovered for further use and processing (Stazi and Tomei, 2018)

UASB reactors are highly effective at retaining the active biomass, and the SRT can be as high as 30 days, with a HRT of 4-8 hours. The reactors are capable of treating influents with high organic loading rates (10 kg BOD/m^3.day), and can be designed for large volumes, with 5 to 20m reactor heights having been used (Tchobanoglous et al., 2014). While it is a well-established process, it is primarily used for the treatment of industrial effluents from the pulp & paper, brewery, and food processing industries, and applications in the treatment of domestic wastewater is still scarce (Tilley et al., 2014)

Advantages of UASB reactors include:

1. High COD removal (80 to 90%)

2. Capacity to tolerate high OLR.

3. Low sludge production and thus less need for desludging.

4. Opportunity to recover biogas for further use (usually scrubbing is required)

5. Easy to build and low investment and operation costs.

6. Good retention of biomass, resulting in high treatment efficiency.

3. Expanded Granular Sludge Bed (EGSB) Reactor - The EGSB is a modified adaptation of the UASB reactor and is commonly characterized by a higher upflow velocity, better recirculation, and a greater height-to-diameter ratio than UASB reactors. The higher upflow velocity helps the EGSB reactor create an expanded bed of the activated sludge particles, which is further facilitated by a taller design (Tchobanoglous et al., 2014). The kinetic energy of the upflow circulation leads to more efficient mixing between the influent and the active biomass, eliminates preferential flows and short circuits due to plugging of matter, and avoids creation of dead zones. EGSB reactors have been found to be effective at removal of soluble substrates, however they are not as efficient as UASB reactors in particulate solids removal as the higher velocity blows them up the reactor and they exit with the effluent (Stazi and Tomei, 2018)

The EGSB reactors are particularly attractive for treatment of low-strength wastewaters where the biogas production rate, and thus the mixing intensity provided by it, is relatively low. The high velocity helps to increase the biomass-substrate contact and enhance the treatment efficiency (Van Haandel et al., 2006). They are also effective at low temperatures of 10C. The upflow velocities may range from 4 to 10 m/h, with high organic loading rates (<35 kg/m^3.d) having been used.

Advantages of EGSB include:

1. Better utilization of reactor volume and mixing characteristics.

2. Can be used for very low-strength wastewaters.

3. Efficient soluble substrate removal.

4. Effective operation at low temperatures.

5. Can be designed with internal circulation (IC) configuration as well, further improving effluent quality.

4. Anaerobic Baffled Reactors (ABR) – The ABR was developed by McCarty and his colleagues at Stanford University, and is essentially comprised of a series of UASB reactors combined into one unit, separated by alternating hanging and standing baffles (Stazi, Tomei, 2018). The liquid flow proceeds horizontally through the different chambers, being directed upwards and downwards by the baffles from one compartment to the other. The sludge biomass remains in the lower part of each compartment, increasing the solid retention and helping achieve greater organic matter degradation. The sludge rises and settles with gas generation in each compartment but moves ahead through the reactor at a sufficiently slow pace to maintain long SRTs of up to 30 days. The generated biogas can be collected from a common area above all the chambers. The higher contact between the active biomass and wastewater enable short HRTs of 6-20 hours (Bajpai, 2017; Tchobanoglous et al., 2014)

Since the ABRs don't need a gas separator, they can be built with shallower depths and thus can be built underground. They are suitable for treatment of low strength wastewaters, and can achieve good COD removal in just a few compartments, resulting in high quality effluents. One major advantage of ABRs is the capability to separate the acidogenic and methanogenic phases in different compartments of the reactor without the need for complex devices or control systems. This phase separation can help boost activity in both the phases up to four times, and improve the hydrolysis of less-biodegradable substrates in the initial compartments (Stazi and Tomei, 2018)

Advantage of ABR include:

1. High retention of biomass – high SRT.

2. Low sludge yields.

3. High tolerance to organic and hydraulic shock loads.

4. Easy to build and operate and requires minimal maintenance.

5. No requirement of special gas or sludge separation apparatus.

5. Anaerobic Membrane Reactors (AnMBR) – AnMBRs are the latest development in the field of high-rate anaerobic wastewater treatment. While membranes have a well-established use for wastewater treatment, AnMBRs first became commercially available in 1980s. The design is simple, with both submerged membranes and external membrane configurations being used. The submerged configuration is more popular, and has been continually researched upon, aiming to improve biogas recovery, and extend the scope for application of the reactors (Skouteris et al., 2012). The combination of membrane technology with anaerobic bioreactors provides a complete retention of biomass, which leads to reductions in the size requirements for the reactor, and helps increase organic loadings. There is maximum removal of degradable soluble organic matter, leading to high quality effluents.

While AnMBRs are highly efficient at COD, SS, and soluble substrate removal, they have several major limitations in terms of cost and process optimization. One of the greatest issues is membrane fouling, which can occur due to the accumulation of particles, colloidal matter, and bacteria on the membrane surface (Bajpai, 2017). This reduces the filtration efficiency, entails frequent cleaning, and reduces the life of the membrane. Techniques used to mitigate fouling include gas scourging, which uses the generated biogas pumped at high velocities to scour the membrane surface, reducing the accumulation of matter. However, the energy requirements for scourging are in the range of 0.6-1.6 kWh/m^3 (Stazi and Tomei, 2018), and thus make the process highly energy intensive. Another major limitation is the high cost of membranes, which leads to higher replacement and maintenance costs (Lin et al., 2013).

The biogas production and wastewater treatment performances of the above detailed reactors are summarized in Table 9.

Table 9 - Biogas production and wastewater treatment performances of anaerobic reactors. Compiled from (Stazi and Tomei, 2018)

Bioreactor Technology	Volume (L)	Operating Temp (°C)	HRT (h)	OLR (kg COD/m³ day)	Influent COD (mg/L)	COD Removal (%)	Biogas Production (Nm³/kg COD removed)	CH_4 production (Nm3/kg COD removed)
AF (Anaerobic Filter)	17	20-25	24	0.32	288	73	0.117	
UASB (Upflow anaerobic sludge reactor)	64000	25.2	4–6		267	50–75		0.19
	12	27.9	8	3	1000	96.5	0.53	
	60000	18-25	23-27		1531	51		0.25
	15.7	25-13	4.7	1.6	312	64-70		0.16-0.26
EGSB (Expanded granular sludge bed reactor)	4.7	15-25	3.5-5.7	1.6-4.5	383-849	73-88	0.28×10^{-3} Nm³/day	
	3	35	6	1.66	150	81	Little or no production	
ABR (Anaerobic baffled reactor)	3000		238		564	58	0.39 mol/h	
	1000	18	12		760	43		0.24
	15	22-28	24	0.669	505-914	82	0.35	
Submerged Anaerobic membrane reactor (Musa et al., 2018)	3	20	12		330-370	90	156	
	15	35	5.3	0.43-0.90	400	90	276	

4.2 Anaerobic digestion for sludge treatment

Sludge is one of the largest constituents of wastewater that is removed during treatment, and its management, including treatment, stabilization, and disposal present a highly complex and expensive problem in the complete wastewater treatment sector. WWTPs incur significant costs and energy expenditure for managing their sludge and its disposal. Sludge management is a multi-faceted problem because of several reasons (Tchobanoglous et al., 2014):

- Sludge contains substances that cause the offensive characters of untreated wastewater.
- The organic matter in sludge is generated from biological treatment of wastewater and will decompose if not treated and handled properly.
- A small portion of the sludge is non-degradable solid matter.

Anaerobically digested sludge is dark brown to black in colour. It has a significant potential to generate biogas and is not offensive to smell when thoroughly digested. The odour is faint, if any, and like that of burnt rubber or hot tar.

Anaerobic digestion of sludge is an important process for sludge stabilization. Some of the other alternatives available are alkaline stabilization, aerobic digestion, autothermal thermophilic aerobic digestion (ATAD), and composting. Anaerobic digestion is the only process that provides the opportunity for energy recovery in the form of biogas generation (Tchobanoglous et al., 2014). Because of the possibility of energy and resource recovery, and the opportunity for beneficial use of sludge biosolids, AD remains one of the dominant processes for sludge stabilization. In addition, AD of municipal wastewater sludge can produce adequate biogas that can meet a large portion of the energy demand of the WWTP operation. Thus, there are multi-faceted advantages for employing anaerobic digestion in the wastewater and sludge treatment lines.

Sludge stabilization is important to achieve the following objectives before proper disposal:

- Reduction of pathogens
- Elimination of offensive odours and gases
- Eliminate the potential for decay and putrefaction

Although sludge stabilization is not a universal practice among WWTPs, a rather large portion of plants with varying sizes and capacities employ some form of stabilization. Apart from the aesthetic and health objectives listed above, sludge stabilization is an effective solution for volume reduction, energy recovery (biogas), and improving sludge dewaterability.

Description of AD processes for sludge stabilization:

Single-Stage High-Rate Digestion: This process is characterized by pre-treatment heating, auxiliary mixing, uniform feeding, and thickening of feed sludge. Sludge mixing can be achieved by a variety of systems, including gas recirculation, draft tube mixers, or pumping. Uniform feeding of sludge is important, and should be pumped continuously to the digester, or in a 30-min to 2-hour cycle. This helps in maintaining constant reaction conditions in the reactor. Since the supernatant is not separated during the high-rate digestion and almost 40-50% of the total solids are digested into gas, the remaining digested sludge is approximately half in concentration compared to the untreated influent feed. Gas storage can be provided by fixed or gas holder floating covers which enables excess gas storage. The digester gas may also be stored in a low-pressure tank separately or compressed and stored.

Two-Stage Digestion: In two-stage design, with the first tank being the primary digester with heating and mixing equipment, while the second tank is used mainly for storage and usually lacks heating facilities. The tanks can be identical, with fixed or floating roof covers. This design is seldom used nowadays due to the additional expense of building a tank which is underutilized and does not provide any operational benefits. Only around 10% of the biogas is generated from the second stage tank. The second stage may be converted into an additional reactor with heating and mixing to help achieve higher stabilization of the sludge before further dewatering or other processing.

Separate Sludge Digestion: Primary and biological sludge is usually mixed together and digested in most WWTPs using anaerobic digestion for sludge stabilization. However, the addition of even small amounts of biological sludge affects the solid-liquid separation of the primary sludge, and the rate of anaerobic reaction is also reduced. To overcome these issues, some WWTPs employ separate digestion of primary and biological sludges in separate tanks. This helps in (1) maintaining the dewatering characteristics of primary sludge (2) the digestion process can be better tuned for the type of sludge being digested. (3) optimized process monitoring, and control can be maintained. It is still an uncommon practice in most plants, and the data for design criteria and performance is very limited for separate biological sludge digestion.

4.2.1 Factors affecting anaerobic digestion

Solid and Hydraulic Retention Times (SRT & HRT): The three constituent reactions of anaerobic digestion (hydrolysis, fermentation, and methanogenesis) are directly affected by the SRT. The efficiency and completion of each reaction is directly proportional to the increase or decrease in the SRT. A minimum SRT exists for each reaction and a SRT lower than the minimum leads to slowdown in the bacteria growth, eventually resulting in the failure of the digestion process (WEF, 2010)

Temperature: The AD process is highly dependent on the temperature, with the microbial metabolic activity, gas transfer rates, and sludge settling characteristics being influenced by the process temperature. It is important in establishing the rate of hydrolysis and methane formation, and the minimum SRT needed to reach a given level of VSS destruction is determined on basis of the operating temperature. AD systems are usually designed for operation in the mesophilic temperature, which is between 30 to 38°C, while some systems can be designed to operate in the thermophilic range of 50 to 57°C. Some processes are designed to carry out the digestion process in separate mesophilic and thermophilic stages (Tchobanoglous et al., 2014)

To have a stable and uniform anaerobic digestion process, it is important to maintain a stable operating temperature in the reactor as the bacteria (especially the methanogenic ones) are highly sensitive to temperature changes. Temperature variations greater than 1°C/day can affect the process performance, and thus it is suggested to limit the variations to less than 0.5°C/day (WEF, 2010)

Alkalinity: The volatile acids to alkalinity ratio is an important metric for monitoring the health status of the digestion process and is generally closely monitored. For well-functioning digesters, this ratio falls between 0.05 to 0.25, and a 0.1 value indicates a good buffering capacity. Alkalinity in the process can be supplemented by adding sodium bicarbonate, sodium carbonate, or lime.

4.2.2 Advanced Anaerobic Digestion Processes

There has been considerable research in improving the performance and efficiency of anaerobic digestion processes. The improved processes can increase the production of biogas and produce high quality biosolids that can be used for further applications. Some of the advanced processes are discussed below and summarized in Table 10 below.

Thermophilic Anaerobic Digestion: Anaerobic digestion which occur between 50 to 57°C is referred to as thermophilic digestion. Thermophilic bacteria are different from mesophilic bacteria and thrive in the higher temperature conditions. Since biochemical reaction rates accelerate with a corresponding increase in temperature, with a doubling of the rates every 10°C, thermophilic digestion proceeds considerably faster than mesophilic digestion. Thermophilic digesters are still relatively uncommon with municipal sludge treatment applications being limited to usage in the first stage of a temperature-phased anaerobic digestion system (Tchobanoglous et al., 2014)

While this has benefits such as the possibility of lower SRTs, improved pathogen destruction, increased biogas production, reduced volumetric requirements, and usage of the same equipment as mesophilic digesters, disadvantages can include higher energy consumption, process instability, higher odour potential, complex heat recovery requirements, susceptibility to foaming, and poor dewatering characteristics of the digested biosolids (Tchobanoglous et al., 2014)

Staged Thermophilic Digestion This process uses a series of two or more anaerobic reactors operating in thermophilic conditions to achieve greater pathogen destruction and reduced pathogen short circuiting. The first reactor is generally large, with the subsequent reactors being smaller reactors. The SRT for the first reactor is usually around 17-22 days, with the following reactors having an SRT of 2-3 days, depending on process requirements.

Staged Mesophilic Digestion Similar to the staged thermophilic process, this process utilizes mesophilic digestion carried out in two-stage mixed and heated high-rate digesters. (Garber, 1982; Torpey and Melbinger, 1967) noted that the benefits of staged digestion included increased volatile solids reduction and increased gas production in comparison with a single-stage digestion process. Recent research in staged mesophilic digestion suggests that the produced biosolids may be less odorous, more stable, and be easier to dewater (Schafer and Farrell, 2000). Typical SRT for the first reactor is 7-10 days, with the subsequent stages designed according to process needs.

Acid/Gas Phased Digestion (AG) digestion process refers to the separation of the three phases of anaerobic digestion – hydrolysis, acidogenesis, methanogenesis – into two separate stages involving different reactors. The first stage is called the acid phase digester, where the hydrolysis and acidogenesis phases occur in an acidic environment. The pH is maintained at 6 or less, and a short SRT is used to provide conducive conditions for generation of a high concentration of volatile acids. The second stage is known as the gas phase and is maintained at a neutral pH and longer SRT to provide suitable conditions for the methanogenic bacteria to survive. This stage is aimed at maximizing gas production. While most AG systems operate with both the stages in the mesophilic range, some pilot tests have been conducted with a thermophilic acid phase and a mesophilic gas phase, with a higher rate of pathogen destruction. Total volatile solids destruction in AG systems ranges from 50 to 60%.

Table 10 - Comparison between advanced AD techniques for sludge. Adapted from (Kalogo and Monteith, 2012)

Technology	Advantages	Disadvantages
Mesophilic High rate anaerobic digestion	Conventional process	Poor dewatering characteristics as compared to raw solid dewatering
	Non-proprietary	Low VS Reduction
	Proven track record in WWTPs	Potential foaming problems
	Most widely implemented process across North America	Longer SRT to achieve desirable VS Reduction compared to the following technologies
Thermophilic high rate anaerobic digestion	Increased reaction rates, smaller digester volumes	Higher operation cost
	Improved VS Reduction	More offensive odours
	Higher gas production	More energy for heating
	Decreased foaming problems	
	Increased pathogen destruction	
	May produce Class A biosolids	
Temperature phased anaerobic digestion	Relatively simple to convert from existing multiple tank system	Patented process (Iowa State University)
	Robust anaerobic design process	higher ammonia levels
	Improved VS Reduction	Produce odorous biosolids during thermophilic digestion
	Requires less reactor volume for same level of VS Reduction	Limited use in North America
	Improved gas production	Limited operation data available
	May produce Class A biosolids	May require more energy
	Control of odours	
Two-phase anaerobic digestion	Reduced foaming problem	Requires more energy for thermophilic temperature if thermophilic stage is applied
	Increased gas production	Produces higher ammonia levels
	May improve dewaterability of biosolids	Limited use in North America
	Improved VS Reduction	Limited operation data available
	May produce Class A biosolids	Produce odorous biosolids during thermophilic digestion if thermophilic stage is applied
	Greater system stability	

An important control parameter for the process is the organic loading rate to the acid phase reactor. This is important to maintain a short detention time and prevent the development of methanogens. Ideally, the detention time should be 1 - 2 days. Due to the short SRT, the loading rate for organic solids ranges in the 24 to 40 kg VS/m3d, which is almost 10 times higher than conventional digestion processes. The gas phase is then designed to be almost 10 days, which may require regulatory approval. There is very little gas produced in the acid phase, and it may be combined with the output from the gas phase, or burned separately.

Temperature Phased Digestion (TPAD) TPAD was developed in Germany to take advantages of thermophilic digestion, while managing the disadvantages by adding a mesophilic stage that helps enhance the sludge stabilization. Thermophilic digestion can be up to four times faster compared to mesophilic digestion. The TPAD process can operate in two modes: thermophilic-mesophilic (T-M) or mesophilic-thermophilic (M-T). In the T-M mode, the thermophilic phase operates at 55C with a SRT of 3 to 5 days, while the mesophilic phase operates at 35C with SRT greater than or equal to 10 days. The overall SRT of 15 days compares to the 10 to 20-day range of the typical single-stage high-rate mesophilic anaerobic digestion process.

The advantages of a phased system vary in each phase. The thermophilic digestion helps facilitate greater hydrolysis of solids, leading to greater volatile suspended solids (VSS) destruction and greater gas production. The VSS destruction can be 15 to 25% more than single-staged mesophilic processes (Schafer and Farrell, 2000) The mesophilic phase aids in destruction of further fatty acids, odorous compounds that are generated in the thermophilic digestion, and improves the overall stability of the digestion process.

4.3 Sludge pre-treatment

Pretreatment of sludge before anaerobic digestion processes helps in increasing the solids loading, the volatile solids reduction, and increases the biogas production. It involves the application of some form of energy to the sludge to increase hydrolysis and breakdown of cell wall to enable better access to the soluble cell matter inside (Tyagi and Lo, 2016). This helps in increasing the availability of soluble matter for anaerobic digestion. There is an improved volatile solids reduction, with a 20-50% increase in biogas production (Maktabifard et al., 2018). These processes can be thermal, physical, chemical, or electrical. These processes can aid in more efficient energy recovery in the form of biogas. A brief overview of different prominent technologies is provided in Table 11. It is important to note that many pre-treatment technologies might have unsatisfactory sustainability performance, so it is important to carefully study pre-treatment processes and their effectiveness before implementing and purchase (Bachmann, 2015)

Mechanical Pre-treatment: These methods use force and mechanical systems to introduce shear stress on the sludge cells or micro-organisms leading to rupture and deformation. This releases the bound organic matter by breaking cellular structures, enabling higher contact with the microorganisms for anaerobic digestion. Most widely used mechanical pre-treatments are extruders and centrifuges working at high pressure, and ultrasound treatment (Ruffino et al., 2015)

Thermal Pre-treatment: Thermal pre-treatment technologies use heat as the energy source to initiate cell lysis. Temperatures ranging from 60 to 200°C and pressures around 10 bars are employed in different technologies to destroy cell structures and release organic matter that can then be available for anaerobic digestion. Advantages include better dewaterability of sludge and decreased viscosity, which helps decrease sludge pumping energy requirements and improves sludge handling (Ruffino et al., 2015). A major disadvantage is the high energy requirement for heating, which can sometimes be balanced with the increased biogas production. Some of the most widely used thermal pretreatment technologies include Cambi™ and BioThelys™ (Kalogo and Monteith, 2012; Tyagi and Lo, 2016)

Biochemical Pre-Treatment: It is also known as two-stage digestion, with the acidogenic and methanogenic stages occurring in two separate reactors. This helps optimize the acidogenic process, enabling better conversion of organic matter into simpler acid compounds. Biochemical pretreatment is used for effective digestion of high-strength industrial wastewaters, or secondary sludge in WWTPs (Bachmann, 2015)

Table 11 - Summary of sludge pretreatment technologies. Compiled from (Tyagi and Lo, 2016)

Technology Name	Description	Developers	Benefits	Reference
Anaerobic Digestion				
Bio-terminator	Mesophilic AD	Total Solids Solution; Research at University of Louisiana, US.	Destruction of 85% TS in 24 h; 93% VS removal at 2 days' HRT	Burnett and Togna, 2007.
Columbus Advanced Biosolids Flow-Through Thermophilic Treatment (CBFT3)	Modified mesophilic AD using plug flow reactor; uses reciprocating engines to produce electricity		Overall energy efficiency of 68-83%; can supply 40-50% of plant electricity requirements	Kalogo and Monteith, 2008
Pre-treatment				
Cambi	Thermal pre-treatment		27% increase in net electricity production reported	Elliot and Mahmood, 2007
	High pressure homgenization of WAS before AD		30% increase in biogas production	Onyeche, 2006
Lysate-thickening centrifuges	Full-scale installation; long term monitoring results		15-26% increase in biogas yield	Zabranska et al. 2006
Ozonation process	Pretreatment of mixed primary and secondary sludge (w/w 1:3.5); ozonation rate - 0.026 kg O3/kg VS	Kurita Water Industries, Japan	Energy production increased by 36% compared to control anaerobic digester	Kalogo and Monteith, 2008
Ultrasonic pretreatment	Sonicated sludge (20 KHz, 200 m3/day) fed to anaerobic digesters (volume 4500 m3, SRT: 30 days)	Singapore	Methane production increased by 45%	Xie et al., 2007
Sonix	Ultrasonic pretreatment of WAS before AD		50% increase in biogas output, short payback period of 2 years	Hogan et al., 2004
Ultrasonic pretreatment	High output ultrasonic reactor (20 KHz)	Sonotronic, Germany	Biogas output increase by up to 50%; methane content increased to 70% CH4)	Tyagi and Lo, 2013

4.4 Co-digestion with other organic wastes

Traditionally, anaerobic digestion has been applied to single substrates for agricultural, municipal or industrial wastes. However, most WWTPs have a 15 to 30% excess digestion capacity that goes unused (Mattioli et al., 2017). With co-digestion, these facilities can improve the digester utilization while increasing biogas production (Tchobanoglous et al., 2014). Co-digestion can be defined as the simultaneous anaerobic digestion of two or more organic substrates, which are mixed together with one being a primary substrate like sludge from WWTPS, and others being secondary substrates such as organic fraction of municipal solid waste (OFMSW).

Co-digestion of fats, oils, and grease (FOG) and OFMSW with sewage sludge has a major potential to improve the biogas production from anaerobic digestion processes in WWTPs (Björn et al., 2017; Holmgren et al., 2015; Iaconi et al., 2017; Nielfa et al., 2015). This is due to the fact that food wastes have a higher organic fraction compared to most AD feedstocks, and, thus, have a higher biogas yield and lower GHG emissions because no resources are needed for feedstock production (Vasco-Correa et al., 2017). There has been considerable research on the effects of co-digestion of different organic substrates along with wastewater sludge, and experiences from full-scale implementations of co-digestion processes in WWTPs are comprehensively reviewed by (Shen et al., 2015). (Koch et al., 2015) have recommend adding up to 35% (based on volatile solids content) of food waste to raw sludge for co-digestion.

(Mattioli et al., 2017) examined a successful case of co-digestion of mixed sludge with municipal solid waste in Rovereto WWTP in Italy. In a 95,000 PE WWTP, co-digestion of 10,000 kg/day of organic waste led to the increase of biogas production from 1321 to 2723 m3/day, doubling the amount of power generated from 3.9 to 7.8 MWh/day. This enabled the plant to recover 85% of their total energy demand.

An investigation by (Koch et al., 2016) into effects of co-digestion of food waste towards energy sufficiency for WWTPs indicated that biogas production can double by addition of 1000 m3 of food waste, while maintaining the same amount of treated thickened raw sludge. (Maktabifard et al., 2018) report that a comparative study of 176 WWTPs in Germany showed that 44% of the plants could achieve energy neutrality by using co-substrates for digestion.

(Björn et al., 2017) analysed the potential for improvement in biogas yields based on the co-digestion of OFMSW with the primary and waste activated sludge (PWASS) from the Henriksdal Wastewater Treatment Plant in Stockholm. They reported a four-fold increase in the biogas production rates in their lab-scale experiment when OFMSW was co-digested with PWASS from the WWTP. They concluded that all the OFMSW generated in Sweden (1,240,000 tons in 2015) could be co-digested in the existing anaerobic digester capacity (339,000 m^3), without upsetting the process performance. An additional 1.2 TWh of biogas could be produced, clearly demonstrating the synergistic effects of co-digesting food waste with sewage sludge from WWTPs.

4.5 Biogas utilization

The purpose of anaerobic digestion in WWTPs is not just to reduce sludge production to facilitate easy handling. Biogas from the AD plants is a useful resource that can be utilized for multiple use cases (Venkatesh and Elmi, 2013). It is important for a WWTP to evaluate the different possible end uses for biogas, and select the option that is most suitable for their site-specific conditions. Different utilization pathways entail different costs and benefits, with varying degrees of environmental and social benefits. Some of the major possibilities for biogas usage are listed below in Table 12.

The gas produced during anaerobic digestion is known as biogas. It contains around 60 to 75% methane (CH_4) by volume, 25 to 30% CO_2, and trace amounts of water vapor, N_2, H_2, H_2S, and other gases. The efficient production of biogas is one of the best indicators of the progress and quality of anaerobic digestion taking place in the reactor, while being a valuable by-product of the digestion process.

Typical gas production values range from 0.75 to 1.12 m^3/kg of volatile solids reduced. It is also possible to crudely estimate gas production on a per capita basis. For WWTPs treating normal strength domestic wastewater, the average gas yield ranges from 15 to 22 $m^3/10^3$ persons•day (Tchobanoglous et al., 2014). There can be wide variations in the gas production rates depending on the biological reaction activity in the digester and the amount of volatile solids content available in the sludge feed.

Gas Pretreatment: Digester biogas has significant amounts of carbon dioxide, hydrogen sulphide, water vapor and other trace gases which usually need to be separated from the biogas before it can be used for heating or energy generation purposes. Such impurities can significantly damage the machinery used for power generation and impact the performance of the system.

Pretreatment for moisture removal can usually be done in the piping system itself. The moisture condenses in the biogas piping system, and with a minimal slope of 10 mm/m, the condensate can be collected at the low points with the help of sediment traps and drip traps. A considerable amount of the moisture can be condensed directly through the cooling achieved in the piping system by exposure to ambient temperatures. Most of the hydrogen sulphide is removed along with the moisture condensate. While this removal can be sufficient for some uses such as boilers, it may still damage piping systems and other equipment used with biogas. Materials like stainless steel or lined ductile iron pipes should be used for piping, as they are resistant to the corrosion caused by the slightly acidic condensate. In the past, wood chips impregnated with iron sponge have been primarily used for sulphide removal. The sulphide reacts with iron to form a solid iron sulphide which can be easily removed.

The most common and beneficial pathway for utilizing biogas is co-generation of heat and power (CHP) using co-generating engines. CHP systems generate heat and electricity at the same time, which is then generally used for the internal demands of the WWTP (Gu et al., 2017a). This is the most advantageous use of biogas for a WWTP, as it helps reduce expenditure on electricity and fossil fuels while improving the plant's sustainability by avoiding emissions. Another popular alternative is to treat the biogas to remove the carbon dioxide and moisture from the gas. The methane content of biogas can be increased from 50-60% to 99%, creating an equivalent to natural gas known as bio-substitute natural gas (Bio-SNG) (Bidart et al., 2014). This 'renewable natural gas' can be injected into the natural gas grid for further use in the gas network, or it can be used as a vehicle fuel for natural gas vehicles. Public transport busses in various Swedish cities utilize bio-substitute natural gas as fuel, thereby replacing usage of diesel and reducing dependence on fossil fuels, and providing a sustainable solution to air pollution (Olsson and Fallde, 2015). Biogas upgradation technologies are still derived from other gas purification and separation technologies developed mainly for natural gas treatment. This leads to a poor development of the market for dedicated biogas upgradation technologies (Makaruk et al., 2010). A suitable technology for biogas upgradation can be membrane gas separation, which can be scale down effectively. (Baker and Lokhandwala, 2008) report that membrane gas separation is economically advantageous when the gas volume flow is low and the CO2 content in the influent gas is relatively high. Biogas from AD falls into these parameters comfortably, and can be upgraded using gas permeation technology, which is a well-developed gas membrane separation process (Cerveira et al., 2018). An additional advantage of gas permeation is that it uses compression for the upgrading process and grid injection, thereby making it more suitable for direct supply to natural gas grid under pressure.

GHG Emissions

It is difficult to estimate the exact GHG emissions from WWTPs due to varied differences in measurement methodologies, system boundaries, and difference in assumed energy source. Specific plant configurations and operational conditions can also affect the direct emissions from the WWTP. Indirect emissions from electricity usage, chemicals consumed, and transportation of materials should be considered as well when evaluating emissions from WWTPs (Maktabifard et al., 2018)

For the scope of this research, the focus will be on emissions reduction due to adoption of biogas recovery and utilization technologies in WWTPs, and the effect they have on the overall sustainability of the treatment plants.

Table 12 - End use scenarios for biogas recovered from WWTPs. (Venkatesh and Elmi, 2013)

Pathway	Description	Impacts	Energy Recovery	End User	Investment
Biogas released without flaring	All methane released into air	Global warming due to methane emissions	No energy recovery	No user	No investment in energy recovery
Biogas flaring	Methane combusted; biogenic CO2 released to air	NOx and SO2 emissions	No energy recovery	No user	Investment for scrubbing for exhaust treatment
Heat recovery	Heat energy used in plant for heating needs	Exhaust gas emissions from combustion; reduced fossil fuel use	Thermal energy	WWTP	Boiler, heat exchanger, piping; O&M expense
Electricity Generation	Electricity generated for use within the plant	Exhaust gases from generator; reduce dependence on grid electricity	Electrical Energy	WWTP	Generator, piping, wiring, pre-treatment of biogas; O&M expense
Combined Heat and Power (CHP)	Electricity generation and heat recovery in CHP engines	Exhaust gases (may be scrubbed); Reduced dependence on fossil fuel and grid electricity	Thermal energy; Electrical Energy	WWTP	CHP engine, piping, wiring, heat exchanger (greater than only heat or electricity recovery)
Sale of Heat	Recovered heat sold outside the plant by piping hot water or steam	Reduction of fossil fuel use for end-users; fuel use for plant may not reduce	Thermal Energy	Proximal users to the WWTP	Same as heat recovery; piping to end-users; Lesser distance is better
Sale of Electricity to Grid	All electricity generated by plant is sold to the grid; Highly unlikely	Total dependence on grid electricity	Electrical Energy	Grid Network	Same as electricity generation within plant; Revenue through feed-in tariff if applicable
Upgrading to vehicle fuel and sale	Biogas is treated and upgraded to bio-synthetic natural gas; sold as automotive fuel	Emissions from diesel use avoided; reduced dependence on fossil fuels for transport system	Mechanical Energy in vehicles	Transport system	Upgrading technology; CO2, H2S, and volatile organic removal; piping; O&M expense; revenue by fuel sale
Sale of crude biogas	Crude biogas is piped to end users as cooking fuel, or sub-contractor for further processing	Dependence on grid electricity and fossil fuel for heating	No energy recovery	Proximal users to the WWTP; sub-contractor	Piping; gas treatment if necessary; revenue through biogas sale

Table 13 - Exhaust gas composition of biogas engine for 1 Nm³ combustion (Abusoglu et al., 2013)

Content	Values
CO_2	207 g
NO_2	400 mg
CO	500 mg
VOC	400 mg
SO_2	9.4 mg

5 Sustainability Assessment for Energy Recovery Systems in WWTPs

Biogas is an important source of energy that can be efficiently recovered during wastewater treatment, and accrue several benefits at the same time such as energy independence i.e. meeting its internal energy demand for the WWTP, use of renewable energy, better effluent quality due to AD treatment, and further environmental benefits due to mitigation of methane emissions. Considering these advantages and the shifting focus on looking at WWTPs as resource recovery centres, there has been a considerable amount of research for analysing the economic feasibility and environmental impacts of implementing and integrating such biogas recovery systems into current and new WWTPs. Since the selection of the right technology and recovery pathway mix for a given plant depends upon a multitude of factors, it becomes important to analyse the available options and choose the most suitable one based on the satisfaction of the project requirements as decided by the stakeholders. In this section, we will look at some of the methods used to analyse biogas recovery systems, and what information is considered important in choosing the right option.

The selection of different technologies can be based on technical, economic, and/or environmental factors. The focus of an analysis can be any combination of these factors, and each factor entails the usage of different methodologies to evaluate them. Several methods have been employed for analysing and selecting the right technology and revenue models to create attractive pathways for recovering and utilizing biogas. While assessing energy recovery technologies and processes, it is important to consider two important factors that must be explicitly analysed. First, the quality standards for effluent wastewater need to be maintained. The effluent standards describe the permissible limits for wastewater quality indicators such as BOD, COD, suspended solids, total nitrogen and phosphorous levels. The EU Council Directive 91/271/EEC concerning urban wastewater treatment specifically states the permissible quality standards of effluent wastewater from European WWTPs. The standard values can be viewed in Table 21. Secondly, the capital costs of energy recovery systems to be added must be economically feasible for plant operators. Thus, it is imperative to refine the energy balance of WWTPs, while optimizing the synergy between effluent quality and energy efficiency (Maktabifard et al., 2018)

5.1 Technical assessment

Technical assessment of biogas recovery systems is a primary requirement to evaluate the potential for biogas generation from wastewater and sludge sources, and identify the optimum technological option based on the context of the particular WWTP. Various methodologies for technical assessments have been applied in published research. Most methodologies follow one of the various methods of assessing biogas potential. These can be laboratory-based, such as Bio-methane Potential (BMP) tests, or theoretical calculations based on well-defined chemical equations, e.g. Buswell-Neaves equation (Jingura and Kamusoko, 2017; Nielfa et al., 2015; Roati et al., 2012). Several equations have been explained in Annexure 1. After evaluating the biogas potential based on the incoming feedstock characteristics, further performance indicators can be evaluated. These can depend on the end-use of the generated biogas, for example, use for combined heat and power (CHP) generation, or use as transport fuel after upgrading to bio-CNG standards (Venkatesh and Elmi, 2013). Various studies have explored the technical feasibility of recovering biogas from wastewater treatment plants at varying spatial scales, ranging from individual WWTPs (Bertanza et al., 2017; Venkatesh and Elmi, 2013), to evaluating nation-wide potentials for biogas recovery (Bidart et al., 2014; dos Santos et al., 2016a).

Bidart and Fröhling utilize a combination of technical assessment using physical, geographical, technical limits, economic limits and a GIS-based approach to evaluate the biogas generation potential of WWTPs across Chile. Using a representative market cost of energy generation to generate supply-cost curves for plants that can generate energy at a better cost than the market price, they evaluated the economic viability of two different biogas utilization pathway: electricity generation in a CHP system, and upgradation of biogas to bio-substitute natural gas (Bidart et al., 2014). The results and analysis from such technical evaluations can be important decision points for driving national policy for tackling wastewater management and sustainable energy issues.

To weigh-in the concerns and objectives (cost, reliability, performance) of various stakeholders (plant owners, citizens, policy-makers, authorities), Bertanza suggests the utilization of multi-criteria decision analysis (MCDA) to account for the various aspects related to wastewater treatment and energy recovery (Bertanza et al., 2017). (dos Santos et al., 2016a) use established biogas potential equations (Lemos Chernicharo, 2007) to evaluate the energy generation potential from biogas recovered in WWTPs across Brazil. By using a contributing population and per capita wastewater generation, they can evaluate the biogas potential, and the financial viability can thus be ascertained. The methodology is concise and does not require specific process data, thereby making it useful for replication for any WWTP connected to a contributing population.

For technical evaluation, (Svanström et al., 2014) developed a methodology for techno-economic-environmental assessment of advanced sludge processing alternatives. They defined several factors and sub-factors that can be used to create a holistic picture of the various aspects of the technology that can be used. Data for these aspects and sub-categories can be either collected from on-site measurements if available or taken from relevant research that can describe the process being studied. A reference plant is defined against which the new solutions can be compared for performance improvements or deterioration. The reference plant is given a fixed score on a scale, for example, a score of 2 on a scale from 1 to 3, with 1 being the worst performance, and 3 being the best. The new solution is then scored according to its performance in comparison to the reference plant. An improvement of 50% or more gets the alternative a score of 3, and a deterioration of 50% of more gets the score of 1. The mean of all aspects is then calculated, and a final score for each alternative is decided, by averaging the score of each individual aspect and giving each aspect equal weightage.

This is a simple method to evaluate several multi-dimensional aspects of a technological system and arrive at a simple metric for comparison with reference systems. This method can also be easily adapted to involve stakeholder views, by arranging for interviews to decide the weightage of different aspects. It can help reflect the requirements of the different groups and tune the results to the local conditions of the project. The various aspects considered by (Svanström et al., 2014) are tabulated below in Table 14.

It is thus visible that a multitude of methodologies exist that can be utilized for technical assessment of biogas recovery systems. Depending on the project requirements and the available data, a suitable methodology can be employed to present data-driven estimates for biogas potential at various spatial scales.

Table 14 - Technical aspects considered for technical assessment along with data source. Adapted from (Svanström et al., 2014)

Aspect	Sub Category
Reliability of the technology	Reliability in terms of variability of WW/sludge characteristics, effluent quality
	No. of full-scale applications in the EU
Complexity and integration with existing facilities	Requires integration with existing systems (e.g. electrical and hydraulic connections)
	Footprint of all equipment needed
	Daily work hours for operation (technicians, specialized workers, and workers
	Safety standards needed
Flexibilty/Modularity	Possibility of modular increase in size
Residues/Recovered materials	Solid/slurry
	Liquid
	Gaseous
Consumption of reagents and raw materials	Fresh water
	Polyelectrolyte
	Coagulants
	Substrate for denitrification
	Pure oxygen
	Methane
	Other
Consumption of electric energy	Quantity
Net production of thermal energy	Type of heat vector (e.g. water, steam, oil)
	Quantity
	Temperature of heat vector
Net production of electric energy	Quantity
Social and authorisation aspects	Public acceptance
	Complexity of authorisation procedures

5.2 Environmental assessment

Life Cycle Assessment is one of the most widely used tools for assessing the environmental impacts of energy and resource recovery systems in wastewater treatment plants. LCA can be defined as "a structured, comprehensive, and internationally standardised method. It quantifies all relevant emissions and resources consumed and the related environmental and health impacts and resource depletion issues that are associated with any goods or services ("products")"

(European Commission - Joint Research Centre, 2010). LCA is effective at considering the direct environmental impacts of a system, such as discharge of effluents, and indirect impacts from input materials and energy, and outputs in the form of waste generated and emissions (Garrido-Baserba et al., 2016). Several studies have noted that the inclusion of LCA in any analysis leads to improvements in the quality of decision making.

There are several categories of environmental impacts that can be monitored during a LCA study, however some are highly relevant in the context of wastewater treatment and energy recovery from wastewater and sludge. Some of the major environmental impact parameters that have been widely used in the literature (Corominas et al., 2013; Garrido-Baserba et al., 2016; Mills et al., 2014; Svanström et al., 2014; Venkatesh and Elmi, 2013; Whiting and Azapagic, 2014) for selecting different energy recovery technologies include:

1. Global warming potential (GWP) – reflects concerns pertaining to climate change

2. Acidification potential (AP) – reflects concerns related acidification of water

3. Eutrophication potential (EP) – reflects issues concerned with excessive addition of nutrients to soil and water

4. Photochemical oxidation – reflects issues of smog creation in urban air

5. Abiotic depletion (fossil) – reflects effects on fossil fuel usage

Among the environmental impacts stated above, global warming potential and eutrophication potential are the two most commonly reported and examined factors in the literature. GWP is an important environmental impact to monitor as it is globally recognized as an indicator of environmental performance and is easily communicable to authorities and regulators. It can also form the basis for receiving carbon subsidies such as Carbon Reduction Commitment (CRC) in the UK (Mills et al., 2014). It is also one of the most widely studied impact categories, and thus is recognized in various social and political discussions as a serious environmental problem (Corominas et al., 2013). Eutrophication potential is another important impact category that is widely evaluated for wastewater treatment systems, as nutrient overloading in water reservoirs and surrounding soil systems can have serious detrimental effects on the marine and terrestrial ecosystems. Corominas et al., in their study noted that 91% of all documents reviewed for LCA studies included eutrophication as an important environmental impact.

For environmental analysis as well, it can be beneficial to normalize or assign weights to the different categories of impacts to make them comparable on the same scale or derive a single-point indicator for overall performance (Rowley et al., 2012). However there have been comments indicating that weighting of environmental impacts can introduce undesired subjectivity into the analysis, and the assignment of weights is more reflective of the decision-making process and the stakeholders' requirements rather than a fair elucidation of the true nature of environmental impacts in a set of technological and design options (Corominas et al., 2013).

It is also important to note the manner in which weights are assigned and the methodology employed in doing so. Rowley, Peters in their review of weighting methods note that there can be two major distinctions in the way weights are assigned. In the first method, weights can be used with compensatory aggregation method, representing substitution rates that describe the potential for trade-offs between different impact categories. The other method entails non-compensatory aggregation and the weights represent importance coefficients, describing the relative importance of the criteria among the different impact categories (Rowley et al., 2012). It is essential for analysts and decision-makers to realize the distinction between these two methods and consider the right option to derive meaningful weights for their context, as it can influence the overall decision-making process and the results derived from it.

Data availability and quality pose another challenge for effective LCA studies in WWTPs. The data for creating the inventory is usually a mixture of experimental or full-scale data and existing published data. This creates a level of variability in the results of different studies, as the accuracy of a study is dependent on its objectives and determines what datasets are sufficient for performing the analysis. It thus becomes crucial to recognize critical factors that can significantly affect the LCA results in evaluating energy recovery systems. To ensure comparability of results and robust quality of studies, it is important to establish mechanisms for sharing results/models/data, and comprehensive supporting information about the detailed inventory should be provided along with scientific publications (Corominas et al., 2013). Creation of standard units for certain major impact categories such as global warming potential and eutrophication potential, and mandatory inclusion of such impacts in studies can help further improve the comparability of different studies.

5.3 Economic assessment

Several methodologies have been applied for economic analysis of energy recovery systems, including biogas recovery. The different methods approach costs and expenses in different ways, with some studies assigning financial value to environmental and social benefits or costs and including them in the economic analysis, while some studies prefer to just evaluate the capital, operations, and maintenance costs of different alternatives. Since most feasibility studies are conducted in the planning phase or examine possibilities of future scenarios, it is not always possible to obtain real-world costs and expenses. Combining cost data from existing research and professional datasets can thus become necessary to evaluate different process configurations.

Another source of complexity in economic analysis is that several factors involved in the analysis are solely qualitative, and thus cannot be quantified or measured. Externalities can be considered such qualitative factors, where externalities are defined as "any consequence (positive or negative) that derives from a project" (Hernández-Sancho et al., 2010). The most widely used parameters of economic analysis are based on capital budgeting methodologies, and can include payback period, net present value, and internal rate of return. Some instances of these parameters being used can be observed in the research by(Mills et al., 2014; Mohammed et al., 2017); the Clean Development Mechanism uses internal rate of return as an important indicator as well (Clean Development Mechanism - UNFCCC, 2019). However, it can be difficult to include and quantify the costs attributed to externalities when evaluating these parameters. As a result, the analysis can unintentionally omit the inclusion of externalities in its findings, instead adopting a more straightforward approach and focusing only on some of the aspects (e.g. either costs, environmental impacts, social aspects etc) (Tomei et al., 2016)

It is mandatory under the Water Framework Directive 2000/60/EC to perform integrated assessment of environmental technologies. Some of the more common methodologies used include comparative cost difference analysis, where cost difference between a reference setup and the experimental setup is used as an indicator of economic performance (Tomei et al., 2016; Venkatesh and Elmi, 2013). Established linear relations or empirical data to determine capital and operations costs can also be used to generate the cost data needed for economic analysis, as shown by (Bidart et al., 2014; dos Santos et al., 2016b; Mills et al., 2014). (Mohammed et al., 2017) note that some of the analytical tools used for economic analysis include Life Cycle Assessment (LCA), Local Economic Impact (LEI), Cost Effectiveness Analysis (CEA), Cost Benefit Analysis (CBA), etc.

CBA has been considered one of the most-widely used economic analysis tools used for environmental projects, where it is also known as Environmental CBA. There is a growing body of research into making CBA more suitable for accurately reflecting the social benefits and costs of environmental projects (OECD, 2018). CBA facilitates aggregation of social, environmental, and economic benefits and costs across different spatial and temporal scales, while finding theoretically sound means to monetize these costs and benefits. (Garrido-Baserba et al., 2016) note that based on the continued use of CBA as a decision-making tool for environmental projects, several economic experts have made efforts towards developing novel approaches for effectively evaluating the economic performance of WWTPs. This includes quantifying the avoided environmental damages in monetary terms, which helps highlight the significance of WWTPs for the environment and society at large. A similar methodology can also be applied to resource recovery systems such as biogas recovery, as they can contribute to significant environmental and social benefits, while enforcing a circular economy perspective.

The cost considerations can include, but are not limited to (Svanström et al., 2014):

- Initial capital cost
- Cost of personnel
- Cost of electricity
- Cost of raw materials and reagents
- Cost for reuse or disposal of solids/residues
- Cost of transportation
- Cost of maintenance
- Income from recovered materials
- Income from electrical energy generation and use/sale
- Income from thermal energy generation and use/sale
- Income from co-digestion of additional substrates (in tipping fees)

5.4 Decision-making tools

As is evident from the above discussions (section 5.1, 5.2, and 5.3) a multitude of methodologies and philosophies have been utilized over the years to enable decision makers to select the most appropriate technological processes and economic configurations for biogas recovery during wastewater treatment. This variability and lack of a standardized approach can be intimidating to non-experts in the fields of industrial management, or process design, and lead to difficulties in theoretically sound decision-making for their own projects. This can include WWTP owners or managers who are looking to upgrade their facilities to recover biogas, or water sector consultants who might not have the necessary knowledge and expertise to evaluate energy recovery systems.

While academic and process research for anaerobic digestion is instrumental in improving biogas yield values and further process optimization, it is difficult for end-users or operators to utilize the research to make informed decisions and choose long-term sustainability objectives. There is a need for preliminary assessment tools that can provide a clear picture of the advantages of implementing sustainability measures such as biogas recovery from wastewater or sludge. Such tools could provide elementary technical, economic, and environmental information using relevant indicators that can help assess the feasibility of such an undertaking, before the comprehensive technical assessment is initiated. It would be advantageous if these indicators can use existing measurements or relevant datasets, without the need for employing additional monitoring and measurement techniques, which can be an additional cost to a plant operator. It can thus be beneficial to develop initial assessment tools that can automate certain difficult sections of the decision-making process. Such tools can take local parameters as inputs, and with in-built calculators designed by experts and based on proven research in the field, provide certain initial assessment parameters that can aid non-expert decision-makers in making well-informed, data driven decisions about implementing the suitable energy recovery system. Several such tools have been developed, with focus on different aspects of the techno-economic-environmental assessment. They are usually developed in the form of easy to navigate spreadsheet tools, with the relevant instructions included along with the data fields, and might include user manuals as well, describing the methodologies used and the assumption data that is used for calculations. Few examples of such simple calculators are available online by companies providing biogas solutions ("Biogas calculator shows energy potential | PlanET Biogas Global GmbH," n.d.), and government organizations that are promoting renewable energy (Renewable Energy Concepts, 2018)

(Wu et al., 2016) developed a calculator to assess the biogas production potential and economic feasibility for farm-based anaerobic digesters in the UK. Their spreadsheet-based calculator is a simple model-based tool that can provide reliable estimates for the available biogas potential based on feedstock specifications and the relevant economic performance indicators. This tool is based on steady-state empirical approaches to measure biogas yields, which are easier to model and calculate for non-experts and end-users, as kinetic models of AD are highly academic and it is difficult to obtain the necessary data and measurements on the field. This approach makes the tool much more straightforward to use and can utilize existing data, making it more viable practically. The tool can calculate biogas yield (biogas output per unit mass of feed material) as a function of operating temperature, retention time, dead time, and type of feedstock.

The Co-Digestion Economic Analysis Tool (CoEAT) developed by the United States Environmental Protection Agency is another good example of such a tool (Rock and Ricketts, 2017). It was developed based on the pioneering research and co-digesting experiences at the East Bay Municipal Utility District, California, where the water utility was able to achieve a 3-3.5 times increase in methane production based on their patented food waste recycling and co-digestion process, as compared to only sludge digestion. The tool is designed as an initial step for assessing economic viability of co-digesting food waste at WWTPs. It is also useful for assessing the feasibility at facilities that do not yet employ co-digestion but would like to explore anaerobic digestion processes. The relative benefits from three end uses of biogas are discussed: electrical energy, thermal energy, and upgradation to CNG for vehicular use. The inputs to the tool include a combination of measured, calculated, and user-fed data, that can then provide the outputs regarding biogas production capacity, generation of biosolids, and related expenses and revenues (Tchobanoglous et al., 2014).

While the CoEAT is a well-designed tool, it has its limitations in that there is no evaluation of environmental benefits. This highlights the need for more holistic approach to designing such decision-making tools for non-experts. An easy access to relevant information regarding the technical, environmental, and financial feasibility can help in the wider adoption and implementation of biogas recovery systems in WWTPs, and help transform them into Water Resource Recovery Facilities (WRRFs). A collection of such preliminary decision-making tools is described in the table below. It is important to note that though these tools might not have a singular focus on biogas recovery, the inputs and results from these tools can be used adapted for biogas recovery system assessments as well.

Table 15 - Decision-making tools used for anaerobic digestion/energy recovery from water. (Compiled by author)

Name of Tool	Developer	Purpose	Source
Life Cycle Assessment Manager for Energy Recovery (LCAMER)	WERF	LCA - spreadsheet tool enabling WWTP operators to assess feasibility of recovering energy from AD of WW solids	Monteith, Kalogo, 2013; WERF, 2018
Novedar_DSS	Univ. Santiago de Compostela	Environmental Decision Support System (EDSS) for improving water and product recovery from WWTPs (Incorporates LCA, CBA, EBA)	Garrido-Baserba, et al., 2016 p. 1099; http://www.novedar.com/en/default.asp
Calculation Tool Carbon Footprint Wastewater Treatment Plant	VA-teknik Södra (Sweden)	Calculation of climate impact	Bachmann, 2015; VA-teknik Södra 2019

Anaerobic Digestion: Decision Support Software	Ireland Environmental Protection Agency	Decision Support System for calculating outputs from various agricultural substrates	(Ireland EPA, 2018)
Co-Digestion Economic Analysis Tool (CoEAT)	US EPA	CoEAT helps users evaluate the costs and benefits of accepting and processing wasted food, fats, oils and greases (FOG) or other organic materials.	Tchobanoglous, 2014; US EPA, 2017
SPIonWeb	TU Graz	LCIA tool for evaluation of environmental impacts (Sustainable Process Index)	Kollmann, Neugebauer, 2017; http://spionweb.tugraz. at/

5.5 Qualitative assessments

LCA, CBA, and other techno-economic assessment methodologies are highly dependent on the quality and availability of data for producing sound results. As discussed above in section 5.4, data availability and reliability issues can introduce variability and make the results hard to compare or standardize. The data scarcity can be due to several reasons, such as prevalence of information with unclear assumptions or hidden biases, supply of technological information from technology manufacturers or interest groups who might inflate figures to display increased efficiency, and lack of existing operating plants whose data can be used for placeholder data for quantitative analysis. In scenarios where such data quality issues exist and limit the scope of conducting theoretically sound quantitative analysis, it can be beneficial to instead opt for qualitative evaluation with stakeholder participation to achieve better participation from stakeholders and gain wider social acceptance of the results from the analysis (Samolada and Zabaniotou, 2014)

SWOT analysis is a well-known qualitative assessment methodology that has been widely used in project management to evaluate the internal and external factors that can work for or against a chosen alternative. In the context of integrated sewage sludge management (ISSM), Samolada and Zabaniotou conducted a SWOT analysis of sustainable sludge-to-energy pathways for Greece. The authors studied sewage sludge incineration, gasification, and pyrolysis as potential pathway for energy recovery, and qualitatively evaluated these 3 technologies based on four guiding criteria that encompassed the essential technical, financial, social, and environmental aspects (Samolada and Zabaniotou, 2014). Such analysis can provide decision-making guidelines for future assessments and can help in designing effective policy instruments and market regulations to allow such pathways to become sustainable in the long run. Similar SWOT analysis for biogas recovery from sewage sludge can be highly beneficial for developing countries to identify their strengths and opportunities in recovering this energy source, and address the weaknesses and threats by taking the necessary measures to mitigate them.

(Venkatesh and Elmi, 2013) use a net percentage methodology to evaluate different technological and cost scenarios with a baseline scenario. The costs for energy recovery scenarios are compared to the baseline scenario, and a net percentage change in positive or negative terms is calculated. Similar methodology is used for environmental impacts like GHG emissions. Then the two bottom lines are weighted and aggregated to reach a single net percentage change value for each scenario.

(Bidart et al., 2014) used physical, geographical, technical, and economic limits to evaluate the biogas to electricity generation potential on a country-scale for Chile. The potentials are plotted in supply-cost curves for 2 alternatives, which makes it easy to visualize the economic feasibility limit for the alternatives, and the subsidy that might be required to make the alternatives feasible for the plants that can achieve the said generation costs.

6 Developed Framework for Sustainability Assessment - Methodological Approach

As discussed in chapter 5, the assessment and selection of different processes for energy recovery is undertaken with a variety of decision-making tools and methodologies. The techno-economic-environmental assessments are based on the underlying principles of sustainability, and aim to enable decision-makers to implement processes and pathways that can satisfy the different dimensions of sustainability, namely technical, environmental, and economic sustainability. Such assessments rely on the definition of adequately pluridisciplinary list of accepted and relevant criteria and indicators (Diaz-Balteiro et al., 2017).

In this section, different indicators that can provide a preliminary understanding of the biogas recovery potential from wastewater and sludge treatment will be analysed. Based on prevalence and usage in existing literature, technical, economic, and environmental indicators have been chosen that can help initiate the discussion between stakeholders towards biogas recovery, without the need for extensive field measurements, which can become an initial barrier for undertaking such feasibility assessments. Firstly, the different types of indicators and their relevance will be discussed. Then the boundary conditions using sustainability indicators will be delineated, and lastly, the sustainability assessment framework using multidisciplinary sustainability indicators will be developed.

6.1 Assessment methodology

A holistic techno-economic-environmental assessment of biogas recovery systems is dependent on the selection of multi-disciplinary sustainability indicators, that can encompass the different sustainability dimensions. Using these indicators, different tools such as multi-criteria decision-making (MCDM), choosing-by-advantages, LCA, NPV, can be integrated together to create a complete techno-economic assessment (Balkema et al., 2002). An iterative process can be utilised to develop the sustainability indicators, and improve their performance based on stakeholder engagements. The process is divided into 3 phases.

In the first phase, the scope of the assessment and the boundaries of the system are defined. This includes the selection and design of sustainability indicators for the energy recovery system, the definition of process boundaries, and the variables and criteria that must be measured to quantify the indicators. Some indicators might be hard to quantify due to lack of data, however, it is better to include such indicators qualitatively to ensure the multi-dimensionality of the assessment.

In the second phase, the sustainability indicators are quantified through information and data collection. The data can then be processed using theoretical or empirical relations for mass and energy balances, cost analysis, emissions calculations, or rated qualitatively. This can be done for just a singular process configuration being investigated, or for several alternatives that are being compared to one another. The indicator performance for each alternative will then be necessary. The indicators can then feed information into the decision-making tools such as choosing-by-advantages, LCA, cost-benefit analysis.

In the third phase, the results from the indicator study and assessment tools are communicated to the stakeholders and the suitability of the process is evaluated based on stakeholder review. The decision-makers can assign suitable weights to the indicators based on their desired objectives from the system and create a composite final sustainability indicator that is based on the weighted average of all the indicators (Molinos-Senante et al., 2014a). A minimum passing criterion can be established to evaluate the feasibility of energy recovery systems. While the normalization and weighting of results is a political process that can introduce variability into the assessment (Balkema et al., 2002; Rowley et al., 2012), it is an essential step to capture the concerns and requirements of the different stakeholders.

An iterative process as suggested by Lundin & Morrison can be used to further optimize the sustainability indicators based on their performance in capturing the various aspects of sustainability, and providing relevant information for decision-making based on data availability and quality considerations (Lundin and Morrison, 2002). Such iterations can include the application of the assessment methodology to different case studies. A simple flowchart shows the assessment procedure as outlined above in Figure 8.

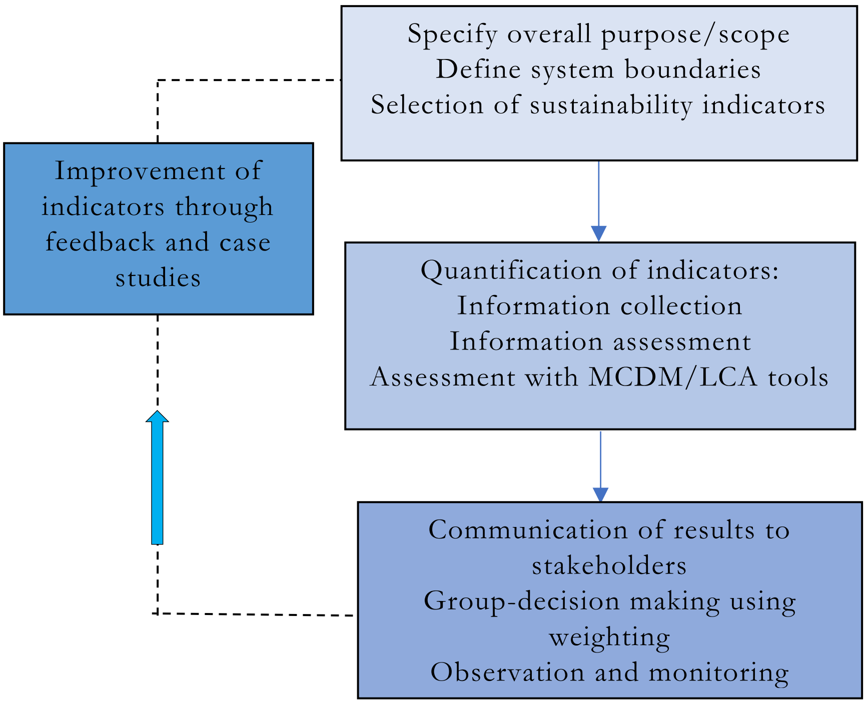

Figure 8 – Flowchart of Assessment Methodology

6.2 Boundary conditions

It has been discussed in previous sections that biogas recovery from anaerobic digestion is possible during wastewater treatment process (section 4.1), as well as the sludge treatment process (section 4.2). High-rate anaerobic reactors like UASB, EGSB, AnMBR, and ABR are used for anaerobic digestion in the wastewater treatment line, while conventional continuously stirred reactors (CSTR) with sludge pre-treatment are more common in the sludge treatment line. The respective technologies can also operate simultaneously on both wastewater and sludge treatment lines, leading to recovery of biogas from both wastewater and sewage sludge. Both the processes have the potential for biogas generation. It becomes important to note this distinction between the two options when assessing the sustainability and defining indicators for the assessment, as methodologies to evaluate biogas potential are different for sludge and wastewater.

To simplify this distinction, two process boundaries are identified. These can be called process-defined boundaries (Lundin and Morrison, 2002), and can be selected with the aim to compare different processes or alternatives. It is important to note that a WWTP might employ biogas recovery from wastewater, sludge, or both the treatment lines, as is described by (Mccarty et al., 2011), the assessment of which would require boundary extensions to include both the lines. The same assessment methodologies can be followed independently for both the processes, and the combined benefits can be reported. These boundaries can be visually described with Figure 9.

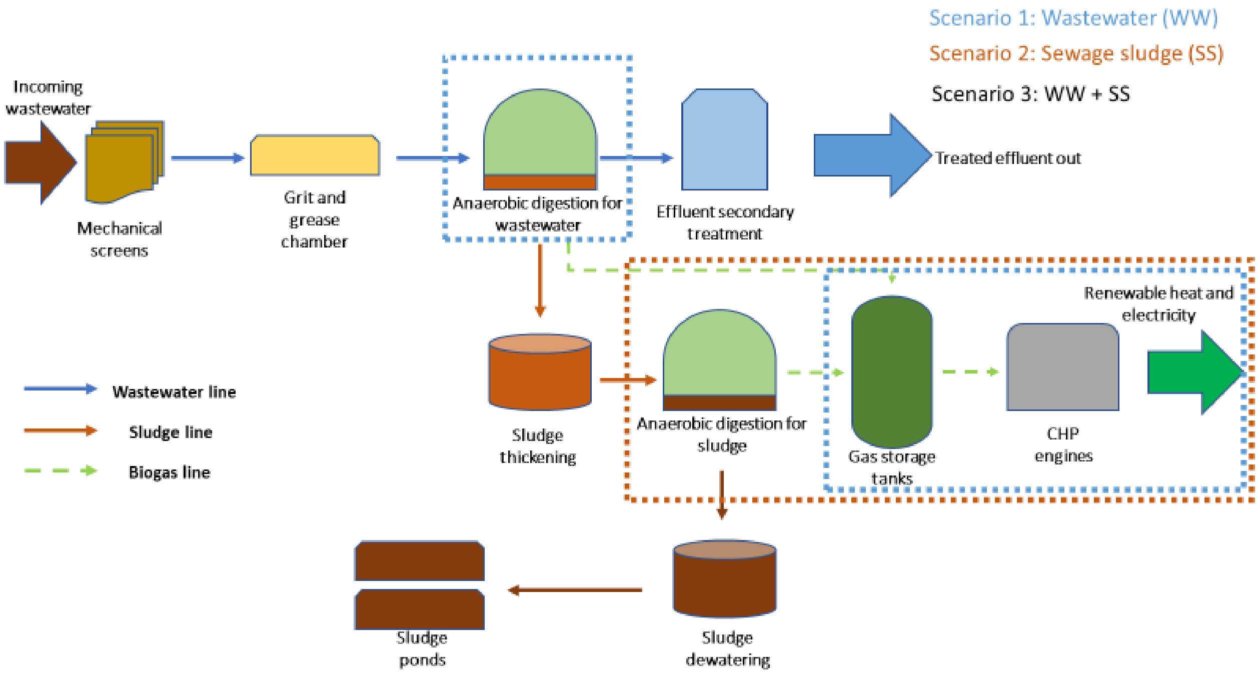

Figure 9 – Boundary conditions for different scenarios (Blue dotted – biogas recovery from WW; brown dotted – biogas recovery from SS) (by author)

The system boundary for biogas recovery from wastewater treatment includes the high-rate anaerobic reactor, the influent wastewater into the reactor from primary settlers, and the treated effluent from the reactor. The biogas produced from the reactor and the energy recovered in the form of electricity and heat are considered in the system boundary.

The system boundary for biogas recovery from sludge treatment includes the influent primary sludge (PS) and waste-activated sludge (WAS) from primary settlers or high-rate reactors, and the sludge digesters. The end uses of the digested and stabilized sludge are not included in this process boundary. The biogas produced from the digesters is the main energetic output, and the produced energy in the form of heat and energy are included in the system boundary. The emissions from the production of energy and any leakages during the operation are included.

6.3 Definition of indicators

Selection of relevant indicators is an essential step of any techno-economic assessment methodology. The selected indicators should be able to elicit the necessary information in standardized units, which can then be fed into the decision-making framework. For biogas recovery, it is important to analyse the various technical, environmental, and economic performances to assess the overall sustainability of implementing such resource recovery systems in new or existing WWTPs. While environmental, economic indicators provide insights into the overall sustainability of the system, the technical indicators are the basis for determining the efficiency and suitability of the system. The rationale for this determining factor is that it is inefficient to invest in a technology or system if the end-user (WWTP operator) is not satisfied with the technical suitability of the solution (Balkema et al., 2002).

A comprehensive review of the various indicators used in assessment of energy recovery systems is presented in Table 16. It is interesting to note that there is a marked absence of a standardized system of units for measuring primary indicators such as biogas generation potential, or electricity generation potential. This results in difficult comparisons and benchmarking of performances between different projects.

Table 16 – Summary of indicators used for assessment of biogas recovery systems. Compiled by author

Indicator Category	Description	Indicator Unit	References
Technical	Theoretical Biomethane (biogas) Production	Nm^3/kg_{COD} (Ruffino); m^3/kg; $m^3/kgVS_{fed}$ (Gianico)	Ruffino, Campo, 2015; Wu, Lovett, 2016; Koch, Plabst, 2016; Gianico, Bertanza, 2015; Balkema, Preisig, 2002; Shen, Linville, 2015;
	Electricity Generation Potential	kWh/m^3; kWh/TDS (Tonne of dry solids); kWh/person.year; MWh/day	Venkatesh, Elmi, 2013; Khiewwijit et al, 2015; Ruffino, Campo, 2015; Singh, Kansal, 2018; Mills, Pearce, 2014 (TDS); [Lundin, Morrison, 2002; Akbulut, 2012 (as energy recovered kWh/person.year)]; Gurieff, Bruss, 2012 (MWh/day)
	Heat Generation Potential	kWh/m^3; kwh/year	Venkatesh, Elmi, 2013; Ruffino, Campo, 2015; Akbulut 2012 (- kWh/year - biogas from manure)
	estimated biogas / methane production rate	m^3biogas/day; m^3 CH4/day (Wu, Lovett); kWh/TDS	Wu, Lovett, 2016; Mills, Pearce, 2014 (TDS);

	Biogas flow produced in anaerobic digesters	m^3/year	Silva dos Santos, Braz Vieira, 2018; dos Santos, Barros, 2016
	Electric Power Potential	MW	Silva dos Santos, Braz Vieira, 2018; dos Santos, Barros, 2016
	Biogas Energy	MJ/d	WERF, 2015
Economic	Economic value of heat generated	€/kWh	Venkatesh, Elmi, 2013; dos Santos, Vieira, 2016 (carbon credits); Svanström, Bertanza, 2014;
	Economic value of elec generated	€/kWh	Ruffino, Campo, 2015; Venkatesh, Elmi, 2013; dos Santos, Vieira, 2016 (Carbon credits); Svanström, Bertanza, 2014;
	Specific cost of electricity generation	€/ kwh	Bidart, Fröhling, 2013; Venkatesh, Elmi, 2013;
	IRR		CDM UNFCCC, 2019; dos Santos, Vieira, 2016; Mills, Pearce, 2014; Mohammed, Egyir, et al., 2016; Akbulut 2012 (biogas from manure)
	NPV		dos Santos, Vieira. 2016; Mohammed, Egyir, et al., 2016; Li, Jin, 2017; Akbulut 2012 (biogas from manure)
Environmental	Avoided Emissions from electricity usage	$kgCO_{2eq}/m^3_{bio}$ ($kgCO2/m^3$wastewater - Khiewwijit)	Khiewwijit et al, 2015; Venkatesh, Elmi, 2013; Silva dos Santos, Braz Vieira, 2018; dos Santos, Vieira, 2016; Singh, Kansal, 2018;
	Avoided emissions from heat energy usage	$kgCO2eq/m^3bio$	
	Global warming potential	$gCO_{2eq}/m^3_{treatedwater}$; $gCO2eq/1000m^3$	Garrido-Baserba, et al., 2016; Lorenzo-Toja, et al., 2015; Mills, Pearce, 2014; Svanström, Bertanza, 2014; Laitinen, Molis, 2017;
	Potential reduction in GHG emissions	ton/yr ; g/m^3	Molinos-Senate, 2014;

Indicators can be an important tool to assess the sustainability performance of resource recovery systems (RRS) applied to wastewater and sludge treatment. They can be designed to reflect both qualitative and quantitative aspects of sustainability, and thus help provide a holistic understanding of the impacts and needs of the system to be adopted. Field measurements, cost calculations, literature reviews, and expert consultations can help acquire the data needed to quantify the indicators. In a sustainability assessment, the stakeholders and decision-makers might want to achieve an objective with the solution. This can either be a maximizing objective, e.g., maximizing biogas production, or a minimizing objective, e.g., minimizing emissions (Balkema et al., 2002). Evaluating different alternatives with sustainability indicators can help select the solution that is best suited to achieve the project objectives. Thus, indicators can serve as 'go' or 'no go' decision variables. The selection procedure can thus be tuned to select technologies that have a specific advantage, or to select technologies that avoid a potential disadvantage.

In theory, indicators should be Specific, Measurable, Attainable, Realistic, Timely (SMART) (Bhaduri et al., 2016). They should be easy to implement and provide policymakers with relevant information about the sustainability performance of the RRS. While indicators may not be able to provide a complete understanding of the various dimensions of sustainability that are involved in the project, it is important that they are designed and chosen in a manner which makes them effective at delivering actionable information that can ultimately aid stakeholder decision making and guide it in line with sustainability principles. The indicators should be unambiguous and clearly signify the impact that they are meant to measure. The variables that quantify these indicators must be comprehensive enough to sufficiently capture the complexity of the system, yet simple enough to be easily monitored and measured (Bhaduri et al., 2016). The development of globally congruent and scientifically verified assessment guidelines for wastewater resource recovery systems can aid in identifying and addressing the interlinkages between the various stressors in the system and their impacts on the various dimensions of sustainability.

6.4 Indicators for sustainability assessment framework

A thorough techno-economic-environmental analysis for biogas recovery from wastewater or sludge can be a resource intensive undertaking for a WWTP looking to recover biogas during their operations. While a thorough LCA and a cost-benefit analysis will be eventually necessary as per environmental and technical regulations, it can be beneficial to obtain a preliminary understanding of the potential volume of biogas that can be recovered, and the energetic and economic benefits of implementation of such a system. This preliminary data can also help gather approval from the various stakeholders to further investigate the scope for biogas recovery in their facility.

As discussed in section 6.3, a set of preliminary indicators that encompass the different dimensions of sustainability and can capture data from existing measurement systems in the plant, or from existing research, are useful for such assessment. They can help provide a clearer understanding of the biogas recovery potential from the existing condition, and help stakeholders take a decision on the feasibility of implementing such a system. To achieve this objective, a set of indicators along with the rationale for their selection has been discussed below in section 6.4.1. Although there are several methods to utilize the biogas generated in WWTPs, these indicators have been chosen with energy recovery using co-generation of heat and power (CHP) as the biogas utilization pathway. CHP is the most widely used method to use the generated biogas, and can be economically viable on a comparatively lower investment (dos Santos et al., 2016a). Based on recommendations by (Molinos-Senante et al., 2014a), these indicators have been selected for their prevalence in existing academic research, and are representative of the crucial information that is at the core of feasibility evaluations. They are transparent, easily quantifiable with well-defined methodologies, and are capable of clearly indicating the performance towards sustainability, or away from it. Detailed descriptions with calculation methodologies about each indicator are presented in Annexure 1.

6.4.1 Technical indicators:

a. **Biogas Generation Potential**: The estimated biogas generation potential from a substrate is the most important technical indicator for biogas recovery systems. It is an essential indicator that has been widely used in research for biogas recovery systems, and can indicate the quantity of biogas that can be generated per unit input, in terms of COD, BOD or volume of influent. The biogas generation potential can be calculated by several methods, some of them being theoretical and some experimental. (Jingura and Kamusoko, 2017; Nielfa et al., 2015) have extensively reviewed the various methods for evaluation of biogas potential, and evaluated the accuracy between theoretical and experimental methods. The theoretical methods are helpful in evaluating the potential for biogas recovery based on just the process efficiency of the existing system or the elemental composition of the influent, thereby precluding the need for extensive laboratory procedures and measurements. While this indicator is widely used, there is a marked lack of a standardized unit and methodology for the reporting of the indicator values, which makes it difficult to compare results from different studies and identify industry best practices.

b. **Energy (Electricity and Heat) Generation Potential**: The energy generation potential from biogas is highly relevant in evaluating the sustainability of the recovery system. Electricity, heat generation using co-generation (CHP) is the most common and economically advantageous usage of generated biogas in WWTPs (Maktabifard et al., 2018). It thus becomes important to quantify the potential electrical and heat energy that can be generated using such a CHP system. Important parameters for evaluation include the CHP system efficiency, calorific value of biogas, the biogas flow rate (Silva dos Santos et al., 2018). The quantification of electricity and heat generation potential can also help quantify the amount of fossil fuels that can be replaced with the generated energy, which can be another important parameter to evaluate in economic and environmental assessments. The energy potential is usually reported in terms of kWh of energy produced per functional unit. However, several functional units such as m^3 of wastewater, tonne of dry solids (TDS), and per capita per year have been noted from literature review.

6.4.2 Economic indicators:

a. **Specific cost of biogas generation:** The cost of biogas generation is an important economic indicator, as it is a direct measurement of the capital needed to recover biogas from wastewater or sludge treatment. It can help capture the cost of recovering biogas per unit volume or person equivalent, and can help compare the economic viability of different biogas recovery technologies. The specific cost can be made up of the initial capital cost of the system, the annual operations and maintenance cost, and the cost of external inputs to the system, if any. It is an important indicator for economic feasibility assessment and is widely used in academic research (Bidart et al., 2014; dos Santos et al., 2016a; Molinos-Senante et al., 2014a). It is necessary to find site-specific cost data, or suitable replacement data from similar case studies to have accurate biogas generation potential.

b. **Economic Value of energy (electricity and heat) generated:** Since electricity and fuel for heating are inputs to the system that is sourced from outside the system boundary, it is an expense to the WWTP. Thus, the generated electricity and heat energy from biogas utilization accrues an economic benefit if used for internal energy needs of the plant. It is one of the main economic benefits of a biogas recovery system, as it replaces an equivalent amount of grid electricity which can be more expensive than the cost of electricity generation from biogas. Similarly, the generated heat energy can help reduce the expenditure on the purchase of fossil fuels or electricity being used for heating energy, thereby accruing an economic benefit to the system In existing research, the economic value of generated energy is used in the evaluation of further derived indicators such as net present value (NPV) (Mohammed et al., 2017). A direct way of evaluating the economic value is to calculate the cost of an equivalent amount of grid electricity and fossil fuel based on the site-specific prices.

c. **Net Present Value (NPV) and Internal Rate of Return (IRR):** NPV and IRR are widely used economic performance indicators, and have been used for evaluating energy recovery systems as well (Akbulut, 2012; Iaconi et al., 2017; Li et al., 2017). The cashflows for each year of the project lifetime are calculated based on the expenses and incomes, and then annualized to the present date using a standard discount rate. The internal rate of return (IRR) is also an important econometric indicator that can help ascertain the profitability of an investment, and is useful for comparing economic performance between different alternatives.

6.4.3 Environmental indicators:

d. **Fossil fuel use avoided:** This indicator is similar to the abiotic depletion indicator used in several LCA studies on biogas recovery and usage (Mills et al., 2014; Venkatesh and Elmi, 2013; Whiting and Azapagic, 2014). When evaluating the sustainability of the system, it is important to understand the quantity and value of fossil fuel usage that can be avoided. It is a major environmental objective to reduce the usage of abiotic fossil fuels, and this indicator can help measure progress towards that goal. Existing studies have used this indicator to varying degrees, using it as feed-in data for abiotic depletion potential (ADP) in LCA (Corominas et al., 2013; Li et al., 2017), or for calculation of economic indicators. However, in our preliminary assessments, it can be an important indicator to convey tangible environmental benefits to stakeholders and decision-makers.

e. **Avoided emissions from electricity usage:** GHG emissions and global warming potential (GWP) are the primary environmental impacts examined in LCAs. As discussed earlier, emissions reduction is globally recognized as an indicator of environmental performance and is easily communicable to authorities and regulators. Analysing and reporting the avoided emissions can also help in qualifying for carbon reduction subsidies. For avoided emissions from biogas generated electricity usage, a methodology followed by dos Santos & Vieira can be used, where the emission factor of the electricity from the local grid is used to evaluate the emissions avoided from reducing usage of grid electricity (Silva dos Santos et al., 2018). Limitations in quantifying the emission factor for the grid can arise due to lack of relevant environmental data for the country. In such cases, UNFCCC methodologies can be utilized to determine the emission factor for the electricity system of a country (Clean Development Mechanism - UNFCCC, 2019, 2015)

f. **Avoided emissions from heat energy usage:** The generated heat energy from biogas can be used for process heat requirements within the plant itself. This helps replace the usage of fossil fuels or electricity that were being used for heating requirements. Thus, there is a tangible reduction of emissions due to fossil fuel usage that can be quantified to study the environmental sustainability of the system.

All the indicators used in the developed sustainability framework are summarized in Table 17 for easy reference. These form the basis for quantitative analysis of the technical, economic, and environmental performance of the biogas recovery system using a combined heat and power (CHP) recovery as the end use of the recovered biogas. While these indicators can assess the sustainability of biogas recovery systems, it may be necessary to examine the quantification methods required based on the choice of biogas recovery technology.

Table 17 – Summary of indicators used for sustainability assessment framework in this study. (Compiled by author)

Indicator Number	Description	Unit
1.1	Biogas flow in Anaerobic Digesters	m^3/year
1.2	Potential Electrical Energy	GWh/year
1.3	Potential Thermal Energy	GWh/year
2.1	Economic Value of electricity generated	€/year
2.2	Economic Value of heat generated - natural gas	€/year

2.3	Levelized cost of biogas production	€/m³ biogas
2.4	Net present value (NPV)	€
2.5	Internal rate of return (IRR)	%
3.1	Fossil fuel use avoided - Natural gas	m^3/year
3.2	Avoided emissions from electricity usage	tCO_2eq/year
3.3	Avoided emissions from heat energy usage - natural gas	tCO_2eq/year

6.5 Using the results from the indicators

The results from the evaluation of the indicators can be expressed in numerical form. To normalize the results from the different categories of indicators and create a composite sustainability value that can be easily comparable for different alternatives, an assessment methodology developed by Bertanza et. al. can be used. (Bertanza et al., 2017) compare the techno-economic-environmental performance of a conventional activated sludge vs Membrane Bioreactor wastewater treatment system, by using a normalization algorithm to assign a score to the result from each indicator, which can be assigned a value of 0-2, with 0 being the least desirable outcome, to 2 being the most desirable. Then, the composite value of each alternative can be calculated by (1) calculating the values of each sustainability indicator, (2) assigning a normalized numerical value, (3) linear combination of the normalized values to reach the overall composite score. It is important to note that this methodology assigns equal weightage to the performance of each indicator, and this will directly influence the overall outcome of the sustainability assessment. This should be kept in mind when comparing alternatives and discussing different sustainability dimensions. Relevant weights can be easily assigned to each indicator to reflect stakeholder interests and preferences through consultations and stakeholder meetings. To assign relevant weights, stakeholders can present their preferred weights for each category of indicators, and a weighting formula can be used, where the final score can be calculated as:

$$F = \frac{(T \times t) + (EC \times ec) + (EV \times ev)}{3} \quad \textit{Equation 1}$$

Where,

F = final sustainability score

T, EC, EV = scores for the technical, economic, and environmental categories of indicators, respectively.

t, ec, ev = weighting factors of the technical, economic, and environmental indicators respectively assigned by stakeholders (sum =3)

These indicators can thus be used to evaluate the economic and environmental benefits from the implementation of a biogas recovery system. While this set of indicators does not aim to encompass a complete LCA or cost-benefit analysis of a system, they can provide important data that can be used as 'go or no-go' decision variables in further pursuing biogas recovery at the WWTP or not. The next step after the quantification of these indicators would be capturing stakeholder preferences with group decision making techniques (Diaz-Balteiro et al., 2017). Different alternatives can be explored to examine the biogas potential and economic benefits from them. A scenario analysis can include co-digestion of different waste streams, complete biogas recovery from wastewater and sludge treatment lines, different reactor configurations, sludge pre-treatment techniques, and different end uses of biogas. Using different combinations of processes and technologies, several scenarios can be compared. The decision-makers can then use a choosing-by-advantages approach to assign importance to each advantage, evaluating each scenario and arriving at a solution that is most feasible for the site-specific application (Arroyo and Molinos-Senante, 2018). It is important to note that social indicators have been excluded from the scope of this set of sustainability indicators. This can be attributed to the fact that these are primarily process-specific indicators, and do not have significant social impacts outside the plant boundaries.

While a wide range of environmental assessments regarding wastewater treatment and resource recovery utilize system-wide or plant-wide Life Cycle Assessment (LCA) methodologies, a comprehensive LCA is out of the scope of this study. The complete wastewater and sludge treatment process is a complex and integrated system with varied material and energy flows that are difficult to map for a preliminary assessment. This study focuses primarily on the potential for recovery of biogas from anaerobic digesters during the treatment of sludge and/or wastewater, and thus, the avoided emissions and other environmental impacts and benefits that can be accrued from this resource recovery process.

7 Case Study Using Developed Sustainability Assessment Framework – Gardabani WWTP, Georgia

This case study is used to demonstrate the practical usage of the indicator-based sustainability assessment framework as developed in chapter 6. The biogas generation potential at Gardabani WWTP is assessed, and the energy potential, the economic performance of the project, and the environmental benefits are quantified using sustainability indicators.

The focus of the field study is on Tbilisi due to several important factors. A major factor is that Georgia is looking at accession to the European Union in the future. Thus, all Georgian laws and regulations are being updated to be in synergy with the EU mandated laws. This has resulted in several important reforms in the water and wastewater sector in Georgia, with sustainable wastewater resource management being a key guiding philosophy. Considering these efforts, IVL and the Swedish International Development Authority have been assisting the Georgian government with updating their water and wastewater sector. Thus, a focus on Tbilisi and biogas recovery from the wastewater system in the city feeds into the existing work on sustainable waste management and utilization of renewable sources of energy. Tbilisi is the largest city in Georgia, and is served by the largest WWTP in Georgia, the Gardabani Wastewater Treatment Plant. Implementing biogas recovery from the WWTP and learning from the experiences can be a model that can be replicated across the country and region.

7.1 Tbilisi overview

Tbilisi is the economic, social, and cultural capital of Georgia, producing almost 48.4% of Georgia's GDP in 2015, and accommodating 30% of Georgia's population. The city was responsible for 63.1% of all formal employment and was the home to 43.6% of all legal entities (278,295) registered in the country (Georgia Water and Power, 2016). It is situated on both the banks of the Mtkvari River and serves as an important power nexus in the region, with a strategic location on the crossroads of Turkey, Armenia, Russia, and Azerbaijan, as well as connecting the continents of Europe and Asia. It's location on the banks of the Mtkvari River coincides with the historical Silk Road. The city is surrounded by hills on three sides and grew in a linear fashion along the length of the river, encompassing an area of around 504 km^2.

Tbilisi is the home to almost half of the urban population of Georgia, as is typical of several ex-Soviet countries, and a key decision factor for policy makers and governing bodies while developing economic measures and urban development policies. The Tbilisi-Rustavi-Gardabani-Mtskheta urban conglomerate dominates the urban national scenario, with only two other cities in the country having more than 100,000 residents: Kutaisi and Batumi. The clear dominance of Tbilisi and the dearth of second-tier cities which are close in scale to Tbilisi creates a disproportionate spread of urban population in the country.

Tbilisi being the largest city in the country, took the initiative on decentralizing the climate change action in 2010, when it became the first city in Georgia to join the European Covenant of Mayors (CoM), which entails a voluntary commitment by the city to reduce their territorial greenhouse gas emissions by 20% by the year 2020. This transition is supported by the Tbilisi Sustainable Energy Action Plan (SEAP) (Covenant of Mayors, 2011), which describes various measures that can be taken to reduce the overall greenhouse gas emissions from the city.

Figure 10 - Tbilisi GDP Distribution by Sector (Tbilisi City Hall, 2018)

7.1.1 Water sector in Tbilisi

Tbilisi being the economic and social capital of Georgia, has a high consumption of water. The average daily consumption of water in Tbilisi was 1.6 million cubic metres as of 2010 (Asian Development Bank, 2016) Upwards of 95% of the urban population in the city has access to improved water sources and sanitation.

The WSS sector services in Tbilisi are provided by the Georgian Water and Power LLC (GWP). The Georgian Water and Power company has a natural monopoly in the WSS sector in the Tbilisi region. It primarily serves the Tbilisi, Rustavi, Gardabani and Mtskheta regions, providing high quality water supply and wastewater services to both industrial and residential consumers in these areas. Due to the high population density in the region, GWP has a customer base of almost 1.4 million people, comprising approximately one-third of the Georgian population (Georgia Global Utilities, 2017). The company owns and operates the complete water services infrastructure including the supply, sanitation, and treatment of water. This includes ownership and operation of collectors, reservoirs, pumping stations, sewage systems, WWTPs, and other required infrastructural elements. The legal customers have water meters installed that are monitored on a cyclical basis. The metering system ensures close to 100% collection of tariffs. At the same time, a significant share of household customers (approx. 75%) remain non-metered and are charged their tariffs based on the number of individuals in the household, and by applying the relevant tariff which is fixed per capita per month. The company was formed in May 2008, when the shares of various companies delivering water supply and wastewater management services in the cities Tbilisi, Mtskheta, and Rustavi were consolidated and sold to Georgian Global Utilities Ltd. (GGU), a complete shareholder of Georgian Water and Power LLC. On privatisation, GWP was formed based on Tbilisis Tskali LLC and Saktskalkanali LLC, which provided water supply services to Tbilisi. One of the major technical obligations of the privatisation deal under the share purchase agreement was the reconstruction and upgradation of the Gardabani WWTP, and an investment obligation of an amount greater than USD 220 million due by May 2018.

The water for supply in Tbilisi, Rustavi, and Mtskheta is sourced from the Zhinvali reservoir (90% of supply) and Mukhrani/Natakhtari aquifer (10% of supply), serving both legal entities and households in the region. There are three reservoirs at

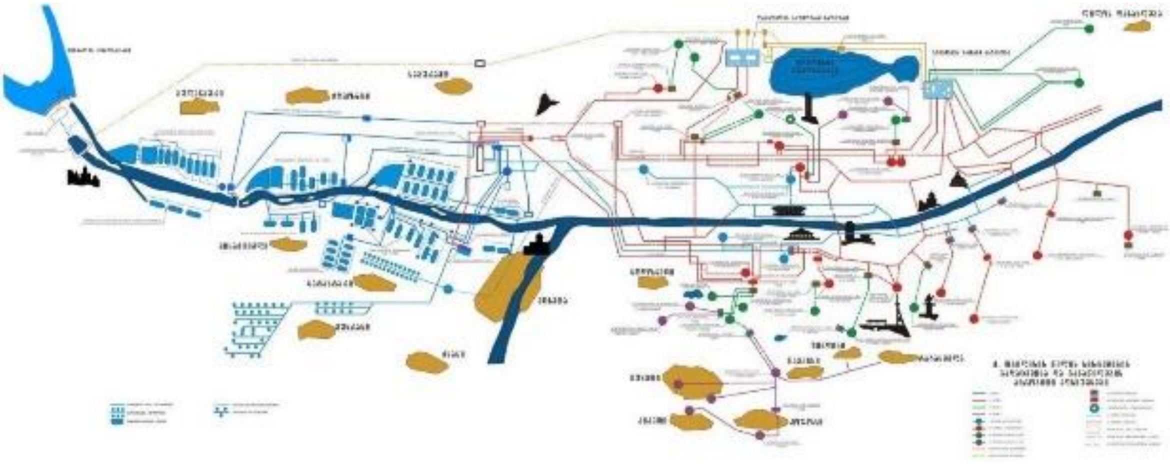

Figure 11 - Tbilisi Water Supply and Distribution System (Georgia Water and Power, 2016)

Zhinvali, Tbilisi Sea, and Bodona, and five conduit systems that serve the city. The water requirements in Tbilisi are fulfilled by utilizing both surface water and groundwater sources. The groundwater is mainly abstracted from the Aragvi Gorge, while the surface water is discharged from the Tbilisi Sea, routed through the Grmagele and Samgori water treatment facilities. Both the facilities have a capacity of delivering 5 m^3 of water per second. The primary treatment of the raw water includes natural sand and gravel infiltration located on extensive land plots situated in the Aragvi Valley, after which the water is sent to the treatment plants at Grmagele and Samgori. After primary treatment, the supply tanks are filled with the treated water. There are 94 reservoirs in the city having a capacity of 320,000 cubic metres and 36 pumping stations in the city ensure uninterrupted water supply and sufficient water pressure for all customers. The water is treated again before finally being distributed to the city districts, and supplied to the various neighbourhoods by over 1000 pumps (Asian Development Bank, 2016). The water supply network in Tbilisi stretches for almost 3,600 km, utilizing supply pipes varying between 13 mm and 1,400 mm in diameter. The branch networks mainly utilize steel pipes, comprising up to 65% of the network, while basic iron pipes make up the remaining 35% of the mains network (Georgia Water and Power, 2016). Polyethylene pipes have been more recently utilized to expand the supply network as well as to repair the old pipes in the existing network (GWP, 2018a).

The quality of drinking water in Tbilisi is monitored rigorously by GWP by an automated system, taking hourly measurements which are controlled by GWP laboratory specialists. All GWP laboratories are ISO-17025 certified. The tap water in Tbilisi is safe to drink, and the quality of drinking water is in full compliance with the World Health Organization (WHO) standards, as well as the national regulation requirements. The quality control is undertaken first at the headworks, including the

Samgori, Grmagele, and Aragvi Gorge stations, and later in the water supply network in the city (GWP, 2018b).

7.1.2 Wastewater sector in Tbilisi

The construction of the wastewater transport infrastructure in Tbilisi originally commenced in 1835. At the time, the sewer system was generally made up of brick sewers, which served as conduits for both drinking water and wastewater. The system was also utilized for collecting rainfall water, joining the Mtkvari river to discharge the surface runoff from the city. Currently, the sewerage system in Tbilisi utilizes pipes with diameters of 150-1200 mm and utilizes several materials including concrete, reinforced concrete, bricks, ceramic, asbestos cement, cast iron, and polyethylene pipes. The drainage system is designed to work with gravity, thus making it self-flowing without the need for additional pumps. The total length of the wastewater collection system is around 1600 km, comprising of a 1000 km of street networks, and 600 km of interquartile and yard network around the city. All the collected wastewater from Tbilisi is run through the sewer system to the Gardabani WWTP. The main trunk sewer has a length of 72km and has 42 separating chambers along the length of the main trunk. It serves as the main transportation conduit for wastewater from Tbilisi to Gardabani.

7.2 Gardabani WWTP

7.2.1 Background

The Gardabani WWTP was constructed in 1986 to treat the wastewater originating from the urban conglomerate of Tbilisi-Rustavi-Mtskheta. It was built as a standard mechanical-biological treatment unit, having a total capacity of treating 1 million m3 of wastewater per day. The initial design of the plant implied a three-step treatment of the incoming wastewater. This included:

- Rough mechanical and primary settlement
- Aerobic/biological treatment
- Secondary Settlement

Until recently, only the mechanical treatment stage of the WWTP was operational, which meant there was no biological treatment of the incoming wastewater and the water was discharged without the removal of harmful biological components. The original layout of the plant includes six cylindrical tanks for methane storage built out of steel and concrete. Though they have physically existed since the initial commissioning, they have never been utilized, and thus represent an immense potential for biogas recovery from the treatment process. Each of these tanks is 23 m in diameter, with a holding volume of 7500 m^3. After primary treatment, the sludge is directly pumped to 10 open stabilization ponds, which are filled sequentially as more sludge gets produced. The stabilization ponds are 200 metres long, 100 metres wide, with a depth gradient ranging from 0.40 m on one side to 1.60 m on the other side. The gradient aids in drainage purposes while the sludge is stabilized in the ponds (Covenant of Mayors, 2011). A detailed schematic diagram of the treatment process can be seen in Figure 14.

Figure 12 - Old satellite picture of Gardabani WWTP before rehabilitation (Source: Google)

The WWTP serves the cities of Tbilisi and Rustavi, the two largest cities in Georgia. In 2005, only 9 million m³ of wastewater was treated in the plant, which accounted for just 74% of the overall volume of wastewater produced in Rustavi and Tbilisi. It is uncommon in Georgia to reuse wastewater for other purposes. One of the most pressing issues existing in the country is the inefficient collection and treatment of industrial wastewater and domestic sewage, which results in untreated wastewater being discharged into water bodies (Asian Development Bank, 2016)

When the Georgian Water and Power (GWP) was formed in 2008, the company signed a share purchase agreement (SPA) with the government, under which the company was required to fulfil certain technical and investment obligations. One of the major obligations was the rehabilitation of the Gardabani Wastewater Treatment Plant, to increase the operational capacity and maintain the rigid quality standards for urban wastewater discharge as laid out in the EU Water Framework Directive (WFD) (Georgia Water and Power, 2016). The SPA also laid out the timeframe for the fulfilment of these obligations, the violation of which subjected the company to certain penalties. The timeframe for the obligations is shown below in Figure 13 and includes the rehabilitation of the Gardabani as the last obligation to be fulfilled. The stipulated timeframe is from September 2016, and as such shows the rehabilitation as still pending. However, as of the time of the field visit, the actual rehabilitation and reconstruction of the plant had been completed, and the testing and handover phases were in progress. An official statement from the company about the completion of the obligation is thus still not available.

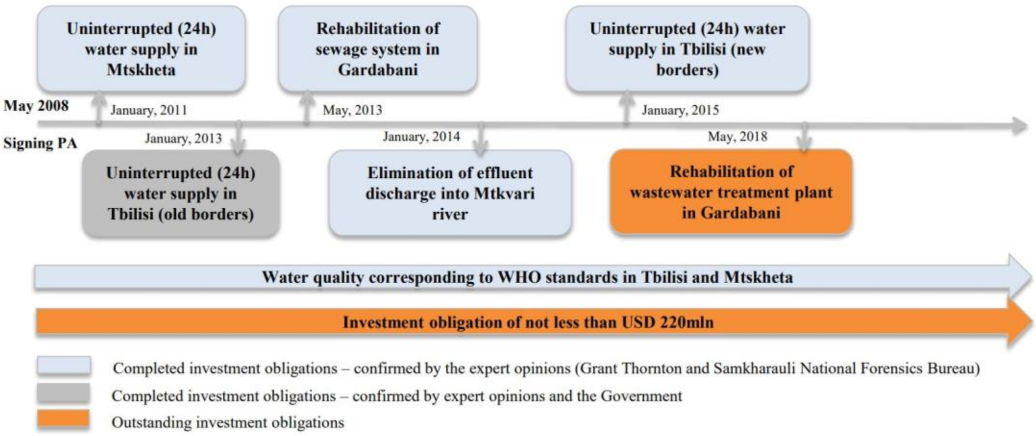

Figure 13 – Obligation status of Georgia Water and Power towards Gardabani WWTP (Georgia Water and Power, 2016)

According to the Georgian legislation, the water discharged from the Gardabani WWTP premises must comply with specified pollutant concentration requirements (stated in Table 18 and Table 21). The GWP management team in negotiations with the MENRP agreed to establish two acceptable levels of pollutant concentration, namely:

- Concentration levels to be achieved before April 2018
- Concentration levels to be achieved after April 2018

The company has stated in their investor prospectus that the mechanical treatment at Gardabani is capable of meeting the specified requirements, thus the rehabilitations and operations of only the mechanical treatment stage will be sufficient to comply with the regulations. However, biological treatment of the water is necessary to maintain the ecological balance in the river and maintain the quality of water to sustain aquatic life.

The pollutant concentration requirements specified by the MENRP are specified as below:

Table 18 - Pollutant concentration levels as specified by the MENRP (Georgia Water and Power, 2016)

Measurement: mg/l	Acceptable level of concentration after 10-April-2018	Acceptable level of concentration until 10-April-2018	Existing concentration in Entering Waste Water (2016)	Expected concentration after mechanical treatment (2016)
Total suspended solids	35	60	56	31
Biological oxygen demand 5	25	40	41	22
Chemical oxygen demand	125		95	87
Total nitrogen	10	20	10	9
Total phosphorus	1	2	0.78	0.65

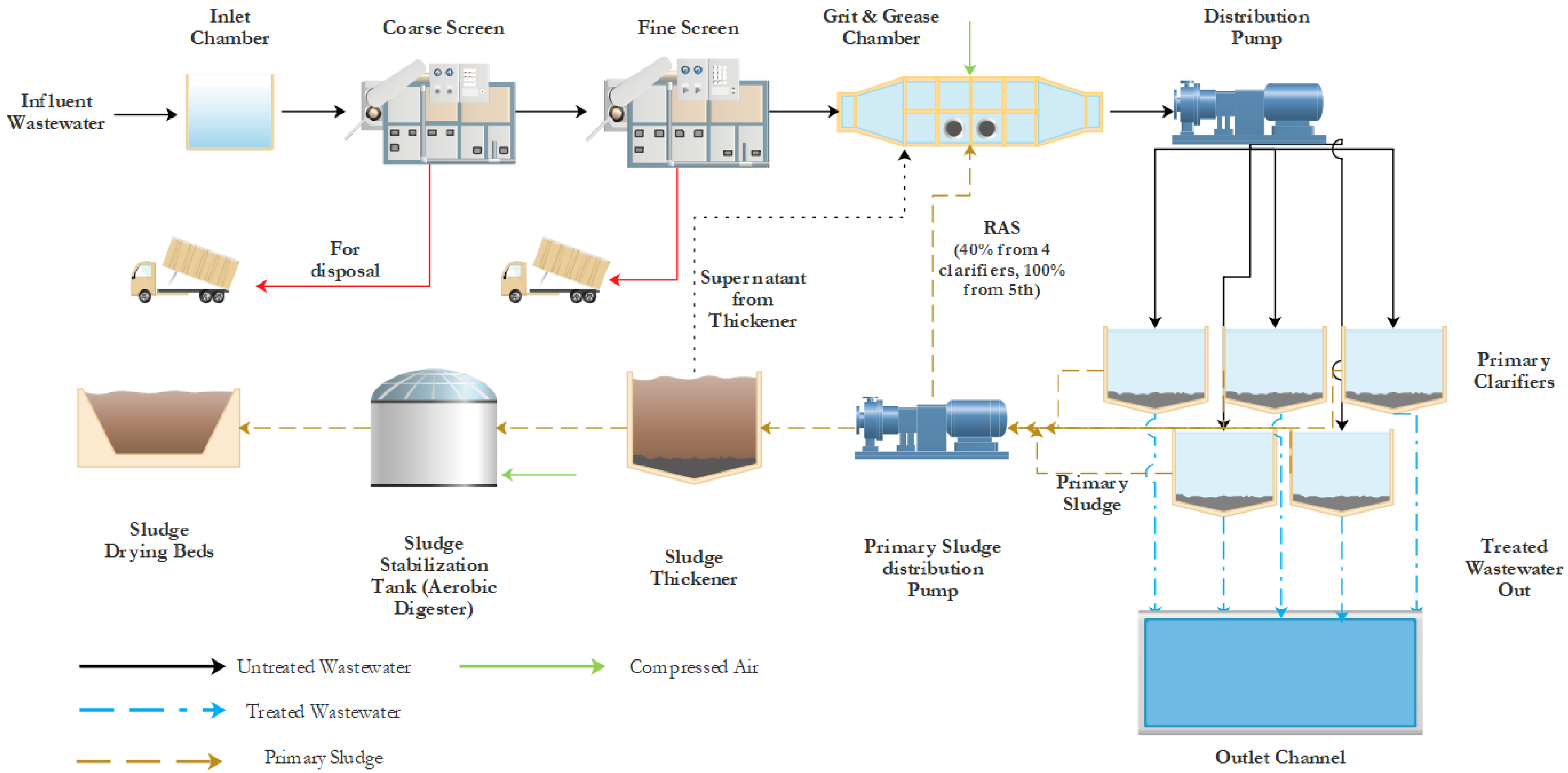

Figure 14 - Process Layout for Gardbani WWTP (Compiled by author)

7.3 Future expansion

The Green City Action Plan for Tbilisi (Tbilisi City Hall, 2017) lays out several strategic objectives for the modernisation of the Gardabani WWTP. This includes a mid-term target of introducing chemical and biological treatment stages in the wastewater treatment process by the year 2025. The Sustainable Energy Action Plan for Tbilisi (Covenant of Mayors, 2011) refers to a Clean Development Mechanism (CDM) project for the upgradation of Gardabani WWTP, however no records of such a proposed project could be found in the CDM database. The project proposed the rehabilitation of the sludge treatment branch to fall in the framework of the designed plant activity, which included re-commissioning of the secondary treatment stage (aeration tanks), and that of the digester for methane production during sludge treatment, as shown in Figure 15.

Furthermore, units for utilization of the methane gas generated in the digester would be installed, including a cogeneration unit for using the gas for electricity generation, as well as flaring the leftover gas. A compactor for sludge from primary and secondary treatment was also proposed (Janelidze, 2006).

It is evident that there is a scope for substantial reduction of methane emissions from the operations of Gardabani WWTP. Georgia's Third National Communication to the UNFCCC (MENRP Georgia, 2015) stipulates that the CH4 emissions from the Gardabani WWTP can rise from a level of 146.2 thousand tCO2eq in 2012, to 239.5 thousand tCO2eq by 2030 (Table 19). However, by employing methane capture and utilization, an emission reduction of almost 191.63 thousand tCO2eq can be realized by 2030 (Table 20).

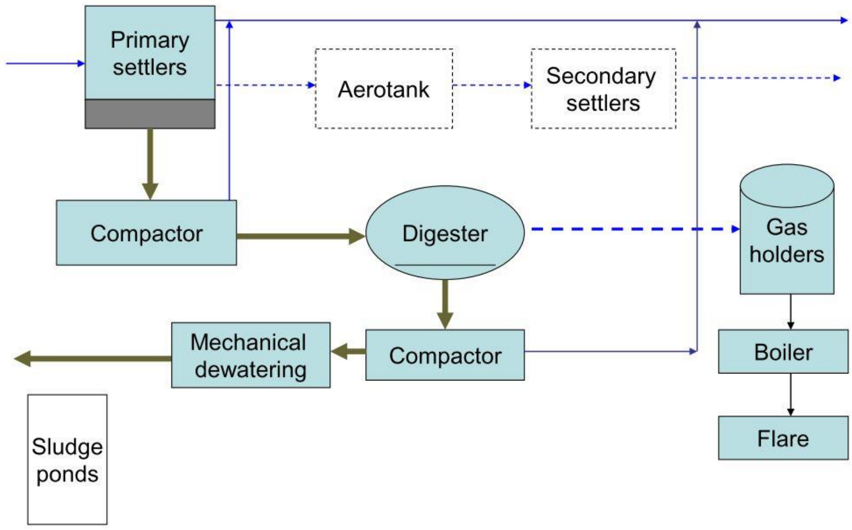

Figure 15 - Proposed plan for methane recovery and utilization at Gardabani WWTP (Covenant of Mayors, 2011)

Table 19 - CH4 emissions from Gardabani and Adila WWTPs (MENRP Georgia, 2015)

City	2012 Emissions ($ktCO_2eq$)	2030 Emissions ($ktCO_2eq$)
Tbilisi (Gardabani)	146.2	239.5
Batumi (Adila)	0	52
Total	**146.2**	**291.5**

Table 20 - Mitigation measures potential from Tbilisi and Batumi WWTPs (MENRP Georgia, 2015)

City	Description of measure	Emission reduction in 2030 ($ktCO_2eq$)
Tbilisi (Gardabani)	Capturing and utilization	191.63
Batumi (Adila)	Capturing and utilization	41.62
Total		233.25

While methane recovery is an important goal for improving the overall sustainability of the wastewater treatment plant, disposal of primary and secondary sludge remains a significant source of waste from the operation of the WWTP. Currently, the sludge from the plant is left in stabilization beds and is not used for any further purposes. However, treated and composted sludge is an effective agricultural fertilizer rich in nutrients and can be sold as an efficient way of utilizing this resource. Some of the global best practices for wastewater sludge reuse/utilization include (Municipal Development Fund of Georgia, 2012):

- Disposal in landfills (as a covering layer)
- Use in agriculture as fertilizer
- Use in landscaping architecture (e.g. for reforestation on erosive soil)
- Use in sustainable forestry cultivating tree-wood
- Use as combustion material after suitable treatment

7.4 Sustainability Assessment for Biogas Recovery in Gardabani Wastewater Treatment Plant

Using the sustainability indicators discussed in chapter 6, a preliminary sustainability assessment for biogas recovery was done for Gardabani WWTP, which serves Tbilisi. Since site-specific data was not available due to data restriction policies of the Georgia Water and Power Company (Melua, 2015), several assumptions and place-holder data were used instead. However, the sustainability analysis does reveal a considerable potential for emissions reduction and electricity production from biogas recovery if it is implemented at the Gardabani WWTP. A comprehensive assessment with on-site data can further reveal the scope for energy recovery and emissions reduction at the WWTP.

Table 21 - Wastewater treatment requirements specified by Georgian Law, EU WFD, and World Bank Guidelines (Municipal Development Fund of Georgia, 2012)

Wastewater Treatment Requirements							
Parameter	**Raw Sewage - range**			**Treated Effluent Standards**			
	Strong	**Moderate**	**Mild**	**World bank Env. Guidelines**	**UWWT/WFD* (2000 - 10000 p.e.)**	**UWWT/ WFD* (> 10,000 p.e.)**	**Georgia (Order N 745; 13.11.2008)**
BOD5 (mg/l) Biochemical oxygen demand	350	250	150	50	25 (70-90% influent reduction)	25 (70-90% influent reduction)	25
COD ((mg/l) Chemical oxygen demand	740	530	320	250	125 (70% influent reduction	125 (70% influent reduction	125
TSS (MG/L) Total Suspended Solids	450	300	190	50	35 (90% influent reduction	35 (90% influent reduction	60
Total P (mg/l) Phosphorous	23	16	10	2	-	2 (80% influent reduction)	2
Total N (mg/l) Nitrogen	80	50	30	10 (Ammonia)	-	15 (70-80% influent reduction0	15

* European Union's Urban Wastewater Treatment Directive

7.4.1 Method and data considerations

Three scenarios were developed to evaluate the biogas generation potential from different plant configurations:

1) biogas recovered only from wastewater (DWW)
2) biogas recovered only from sewage sludge (SS)
3) biogas recovered from both wastewater and sludge streams (DWW+SS)

Each scenario models the annual potential biogas generation from 2018 to 2040. The influent wastewater flow is computed based on the contributing population for Tbilisi. The increase in wastewater generation in Tbilisi is modelled based on the per capita wastewater generation of 0.39 m^3/capita/day (from Gardabani WWTP Field Visit), which is taken to be constant through the modelling timeframe. Using the population progression suggested by (Meladze and Loladze, 2017), the population is linearly extrapolated until 2040 and is assumed to increase from 1.16 million in 2018 to 1.46 million in 2040. A similar methodology has been employed by (dos Santos et al., 2016a) to evaluate the biogas potential from WWTPs in Brazil. An Upflow Anaerobic Sludge Blanket (UASB) reactor is assumed to be the anaerobic digestion technology for biogas recovery from wastewater. The sustainability indicators were then calculated for each year based on the biogas output for the respective years.

For evaluating the biogas generation potential from sewage sludge (SS), an approach from (Andreoli et al., 2007) is used. The biogas potential is estimated through the mass and energy balance in an anaerobic sludge reactor, where the biogas generation is dependent on the volume of volatile solids (VS) destroyed. A value of 0.95 m^3 biogas/kg VS destroyed is taken from (Andreoli et al., 2007). Detailed formulae are explained in Annexure-1. Since site-specific data was not available due to data restriction policies of the Georgia Water and Power Company (Melua, 2015), important factors and data was adopted from relevant academic studies (Akbulut, 2012; Bidart et al., 2014; dos Santos et al., 2016b; Lemos Chernicharo, 2007). The influent wastewater characteristics are referenced from the wastewater treatment requirements specified by Georgian Law, EU WFD, and World Bank Guidelines (Municipal Development Fund of Georgia, 2012) and are used for defining the COD influent and effluent rates from the UASB reactor. Using the value obtained for biogas potential in anaerobic reactors, the electricity and heat generation potential can be calculated as described in Annexure 1. The electricity and heat are assumed to be generated simultaneously in a CHP engine. The electrical and thermal efficiencies of energy conversion are assumed to be 33% and 45% respectively. A list of values used for evaluating the indicators are stated in Table 22 below.

Table 22 – Parameters used for evaluating biogas potential and sustainability indicators for Gardabani WWTP (Compiled by author)

Parameter	Unit	Quantity	Source
For average influent flow (m^3/year)			
Contributing population in 2018	Inhabitants	1160000	(Meladze and Loladze, 2017)
Wastewater generation per capita	m^3/inh.day	0.39	Local sources
For volumetric correction factor for temperature f(T)			
Atmospheric pressure (P)	atm	1	(dos Santos et al., 2016a)
Average ambient temperature (T)	K	298	
COD consumed for 1 mol of CH4 produced (K)	g COD/mol	64	
universal gas constant - R	atm.L/mol.K	0.08206	
Volumetric Correction factor for temp f(T)	g COD/L	2.61717159	
For biogas generation potential (m^3/year)			
average efficiency of COD removal (η)	%	59%	(dos Santos et al., 2016a)
COD influent - (S_0)	(kg/m^3)	0.74	(Municipal Development Fund of Georgia, 2012)
COD effluent - (S)	(kg/m^3)	0.125	
Solid production yield - (Y)	(kg COD_{sludge}/kg COD_{in})	0.17	(Lemos Chernicharo, 2007)
concentration of methane in the biogas - C_{CH4}	%	60%	
loss index of gas in the reactor due to leakage or dissolution of the gas in the liquid effluent (I_L)	%	40%	

For biogas generation potential from sewage sludge (m^3/year)			
Mass of sludge directed to the sludge treatment stage (after CAS, UASB)	gSS/inh.d	70 ; 15	(Andreoli et al., 2007)
Sludge dry solids content (after CAS, UASB)	%	1.5% ; 4.5%	
Density of thickened sludge	kg/m^3	1020	
Volatile-to-total solids ratio (after CAS, UASB)		0.775 ; 0.575	
Biogas produced per unit volatile solid destroyed	M3 biogas/kg VS destroyed	0.95	
For electric power and electrical energy (KW, GWh/year)			
Lower heating value of methane (LHV)	MJ/m3	35.5	(SGC, 2012)
Efficiency of the energy conversion technology	%	0.33	(dos Santos et al., 2016a)
concentration of methane in the biogas - CCH4	%	0.6	
Factor for unit adjustment		31536	
Capacity factor of annual operation of the power plant		0.8	
For thermal energy (GWh/year)			
Total energy value of biogas	kWh/m^3	5.5	(SGC, 2012)
Thermal Efficiency		0.45	(Akbulut, 2012)
Lower Calorific Value of Natural Gas	kWh/m^3	11	(SGC, 2012)
Energy Content of Diesel	kWh/L	9.8	(SGC, 2012)
For emissions reduction potential (tCO_2/year)			
Grid emission factor - Georgia	tCO_2/MWh	0.459	(Institute for Global Environmental Strategies, 2019)
Emission Factor for natural gas	tCO_2/GWh	55.035	(Ministry of Environment Protection of Georgia, 2016)

7.4.2 Process considerations

In the first scenario, biogas is recovered only from the wastewater stream with the aid of a UASB reactor. The effluent from the primary clarifiers is assumed to be sent to the UASB reactor which is maintained at mesophilic conditions. In the second scenario, biogas is recovered only from the sludge stream at the WWTP after following a Conventional Activated Sludge (CAS) process. Both primary sludge (PS) and waste activated sludge (WAS) are assumed to be digested in a single stage mesophilic digester. The third scenario assumes biogas recovery from both the streams, assuming that the sludge from UASB reactor is further sent for digestion in a mesophilic anaerobic sludge digester. Since sludge production from a UASB reactor is comparatively lesser than that after CAS, the biogas output is also affected accordingly. The incoming wastewater flow remains the same in all three scenarios. For all three scenarios, it is assumed that all the generated biogas is utilized for electricity and heat generation in a CHP system. No pre-treatment of the biogas is considered, and the digestate is assumed to be sent to the sludge drying beds available on-site. It is assumed that the generated electricity will be utilized within the WWTP and will replace the grid electricity usage. Similarly, the heat energy is assumed to replace natural gas usage in the WWTP for heating purposes. While there are no processes currently in the WWTP that utilize heating, it is assumed that the inlet wastewater and sludge will be heated before being fed to the UASB reactor to maintain mesophilic conditions. Additional heat energy can be transferred to nearby industries (power plants) and can become a source of revenue for the WWTP.

Table 23 – Local cost data for Gardabani WWTP (Compiled by author)

Description	Unit	Value	Source
Electricity Tariff	EUR/kWh	0.041	(Telasi, 2019)
Natural Gas	EUR/m^3	0.14	(Agenda.ge, 2018)
Diesel Price	EUR/L	0.73	(SOCAR, 2019)
CER Rate	EUR/tCO_2	2.16	(Hamrick and Gallant, 2018)

For assessing the financial viability for each scenario, the Net Present Value (NPV) and Internal Rate of Return (IRR) were evaluated over the project lifetime. A discount rate of 10% was adopted, a standard for assessing bioenergy systems (Campbell et al., 2018) and the project lifetime is taken to be 22 years (2018 to 2040). The costs and revenues considered for financial assessment are stated in table 23. Cost data for UASB reactors was sourced from (Sato et al., 2007), and cost data for CHP systems was sourced from (dos Santos et al., 2016a). All the cost data was converted to 2018 EUR for standardization. For biogas recovery from sludge digestion, capital and operational cost data from (Bidart et al., 2014) was utilized. The capital costs from these sources include the cost of building the supporting infrastructure as well. Since the WWTP is already operational with most of the infrastructure and systems in place, it was assumed that 40% of the capital cost is the technical cost of installing the biogas recovery systems (COWI et al., 2004; CSE India, 2019). The operations and maintenance (O&M) costs comprise of the electricity, manpower, repairs, and chemical costs (Sato et al., 2007). The initial investment is assumed to be invested completely in the first year, although developmental funding and grants from financial institutions can help split the capital into instalments that can be paid over the project lifetime. This can also improve the Net Present Value of the project. The generated electricity is assumed to replace grid electricity and thus has been assigned an economic value equal to the local price of grid electricity in EUR/kWh. Similarly, the generated heat energy is assumed to replace natural gas and has been assigned an economic value equal to the local price of natural gas in EUR/m^3. To quantify the environmental benefits of emission reductions, a Certified Emissions Reduction price of 2.16 EUR/tCO_2 is assigned based on published data on voluntary carbon markets (Hamrick and Gallant, 2018). It is assumed that the digestate is not utilized further for any beneficial use and thus does not add any revenue to the plant. Utilizing the digestate as a soil conditioner or for further resource recovery can provide additional sources of income for the WWTP. Due to lack of historical prices of fuels and electricity in Georgia to evaluate a growth trend in prices, the prices have been assumed to be uniform through the project lifetime.

Table 24 – Costs and revenues considered for financial analysis

Costs	Revenues
Initial Capital	Electricity Sales
Annual O&M	Heat Sales
Electricity Consumption	Carbon Credits
Heating Fuel	

Table 25 – Cost data sources for scenarios (Compiled by author)

Description	Unit	Formula	X Component	Unit	Source
			UASB Costs		
Capital Cost	USD/m^3/day	$494*x^{-0.2}$	Average daily influent flow	m^3/day	(Sato et al., 2007)
O&M Cost	USD/m^3/day	$457*x^{-0.49}$	Average daily influent flow	m^3/day	(Sato et al., 2007)
			Sludge Costs		
Digester Capital Cost	EUR	$I = 18248*x^{0.8586}$	Hourly methane production	m^3 CH_4/hour	(Bidart et al., 2014)
Energy Generator Capital Cost	EUR/kW	$I = 15648.x^{-0.536}$	Electric Power	kW	
CHP O&M Cost	ct EUR/kWh	$C = 17.053*x^{-0.478}$	Electric Power	kW	

Environmental indicators are quantified by calculating the scope of emissions reduction by decreasing the use of grid electricity and fossil fuels in the WWTP (dos Santos et al., 2016b). For emissions avoidance from decreasing grid electricity use, the emission factor for grid electricity in Georgia is utilized. A grid emission factor 0.459 tCO_2/MWh was taken for the Georgian grid (Institute for Global Environmental Strategies, 2019). It was assumed that diesel or natural gas are the fossil fuels used for heat generation requirements in the WWTP. While the total amount of fossil fuel use in the plant could not be obtained, the decrease in fossil fuel use can be calculated. For emissions avoidance from decrease in fossil fuel use, the emission factors for stationary combustion of diesel and natural gas were used. Emission factor for natural gas was considered to be 55.03 tCO_2/GWh (Ministry of Environment Protection of Georgia, 2016). Further information about calculation of indicators is available in annexure 1.

7.4.3 Results from sustainability assessment

The scenario analysis reveals a considerable potential for biogas recovery in Gardabani WWTP. While it is evident that biogas recovery from both wastewater and sludge streams will have the greatest biogas output (Scenario 3 - 810 million m^3 over lifetime), there is only a slight advantage over biogas recovery from just wastewater (Scenario 1 - 767 million m^3 over lifetime). This is due to the fact that sludge production after treatment in UASB reactor is almost 80% less than the volume of sludge produced after CAS process (Andreoli et al., 2007). The volatile solids available in sludge after UASB are also reduced, limiting the available VS in the sludge anaerobic digester, and reducing biogas output. This can be countered by co-digesting additional substrates such as municipal solid waste, agricultural residue, or waste from food processing industries. Scenario 2 has the lowest biogas output over the project lifetime, with a total biogas generation of 270 million m^3. The overall production values can be seen in Figure 16.

Considering the average annual biogas potential over the project lifetime, scenario 1 can provide 33 million m^3 biogas annually. This biogas can help generate an average of 52.11 GWh of electrical energy and 78 GWh of thermal energy annually.

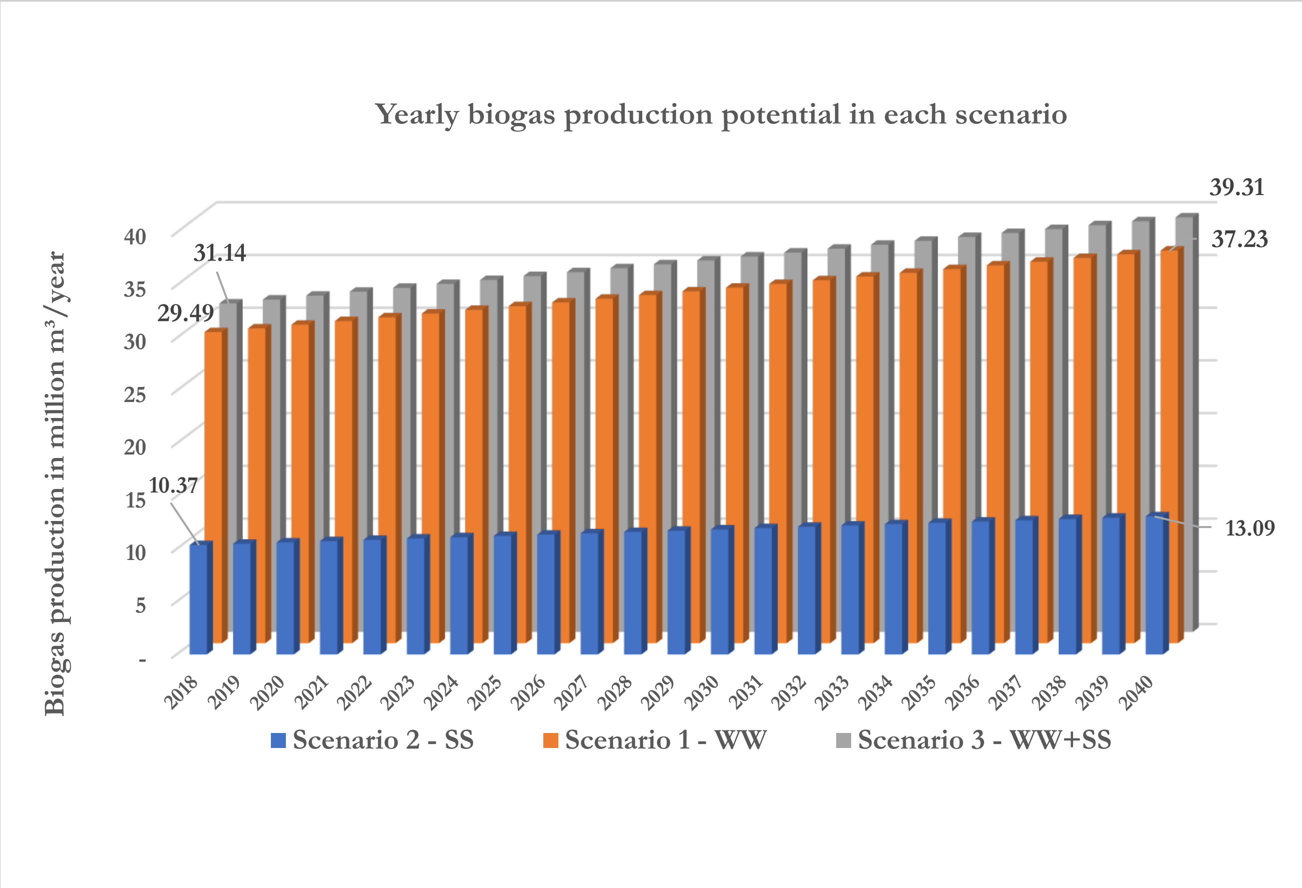

Figure 16 - Summary of biogas potential and sustainability indicators for Gardabani WWTP

Table 26 – Results from sustainability assessment of biogas recovery from Gardabani WWTP

Sr. No.	Indicator Description	Unit	Scenario 1 - WW	Scenario 2 - SS	Scenario 3 - WW+SS
	Technical Indicators				
1.1	Total lifetime Biogas Flow in Anaerobic Digester	m^3	767,268,861.88	269,826,451.71	810,167,537.39
1.2	Average Annual Biogas Flow in Anaerobic Digester	m^3/year	33,359,515.73	11,731,584.86	35,224,675.54
1.3	Total lifetime potential for electrical energy	GWh	1,198.47	421.47	1,265.48
1.4	Average annual potential for electrical energy	GWh/year	52.11	18.32	55.02
1.5	Total lifetime potential for thermal energy	GWh	1,795.41	631.39	1,895.79
1.6	Average annual potential for thermal energy	GWh/year	78.06	27.45	82.43
	Economic Indicators				
2.1	Levelized cost of biogas production over lifetime	EUR/m^3	0.06	0.12	0.07
2.2	Lifetime economic value of generated electricity	EUR	49,137,432.45	17,280,225.62	51,884,749.43
2.3	Average economic value of generated electricity	EUR/year	2,136,410.11	751,314.16	2,255,858.67
2.4	Lifetime cost of equivalent thermal energy from natural gas	EUR	22,850,661.74	8,035,922.33	24,128,262.30
2.5	Average annual cost of equivalent thermal energy from natural gas	EUR/year	993,507.03	349,387.93	1,049,054.88
2.6	Certified Emissions Reduction (CER) Benefits over lifetime	EUR	1,401,645.36	492,918.47	1,480,012.59
2.7	Average annual CER benefits	EUR/year	60,941.10	21,431.24	64,348.37
2.8	Net Present Value of biogas recovery costs (NPV)	EUR	7,904,749.42	-3,493,743.74	5,408,738.16
2.9	Internal rate of return (IRR)	%	18%	5%	15%
	Resource and Environmental Indicators				
3.1	Total lifetime emissions avoided by electricity generation from biogas	tCO_2	550,099.55	193,454.23	580,856.10
3.2	Average annual emissions avoided by electricity generation from biogas	tCO_2/year	23,917.37	8,411.05	25,254.61
3.3	Total lifetime natural gas equivalent for thermal energy	m^3	163,219,012.44	57,399,445.18	172,344,730.68
3.4	Average annual natural gas requirement for equivalent thermal energy	m^3/year	7,096,478.80	2,495,628.05	7,493,249.16
3.5	Total lifetime emissions avoided by replacing NG with thermal energy generation from biogas	tCO_2	98,810.34	34,748.76	104,334.91
3.6	Average annual emissions avoided by replacing NG with thermal energy generation from biogas	tCO2/year	4,296.10	1,510.82	4,536.30
3.7	Total lifetime combined emissions avoided (3.1+3.5)	tCO_2	648,909.89	228,203.00	685,191.01

The combined scenario 3 (DWW+SS) has the highest biogas generation potential, generating a total of 810 million m³ of biogas over the project lifetime, with an average annual generation of 35 million m³. The maximum value of generated electricity is 1265 GWh in the combined (DWW+SS) scenario 3, with a total economic value of 51.88 million EUR over the project lifetime, considering the local electricity tariff of 0.041 EUR/kWh (Telasi, 2019). Electricity generation in the SS scenario is the lowest, with a total of 421.47 GWh of electricity generation over 22 years. For thermal energy, a local natural gas price of 0.14 EUR/m³ is considered (Agenda.ge, 2018). With respect to thermal energy, combined heat recovery in scenario 3 (DWW+SS) has the potential to generate 1,895 GWh of heat energy over the project lifetime, with an average annual generation of 82.43 GWh. This can help avoid the usage of 172.34 million m³ of natural gas worth 24.12 million EUR. The lowest heat energy generation capacity is from the sewage sludge scenario (SS), with a total thermal energy generation of 631.4 GWh over the project lifetime, and fuel savings worth 8.03 million EUR. The generation and economic benefits in all three scenarios can be compared in Figure 17 and Figure 19. These cost calculations are based on the local prices of electricity and natural gas in Tbilisi. It is possible that a combination of fossil fuels is used for thermal energy generation in the WWTP. The cost of fossil fuels will then be split proportionately. The sustainability indicators for all scenarios are tabulated in Table 26 for easy reference and comparison.

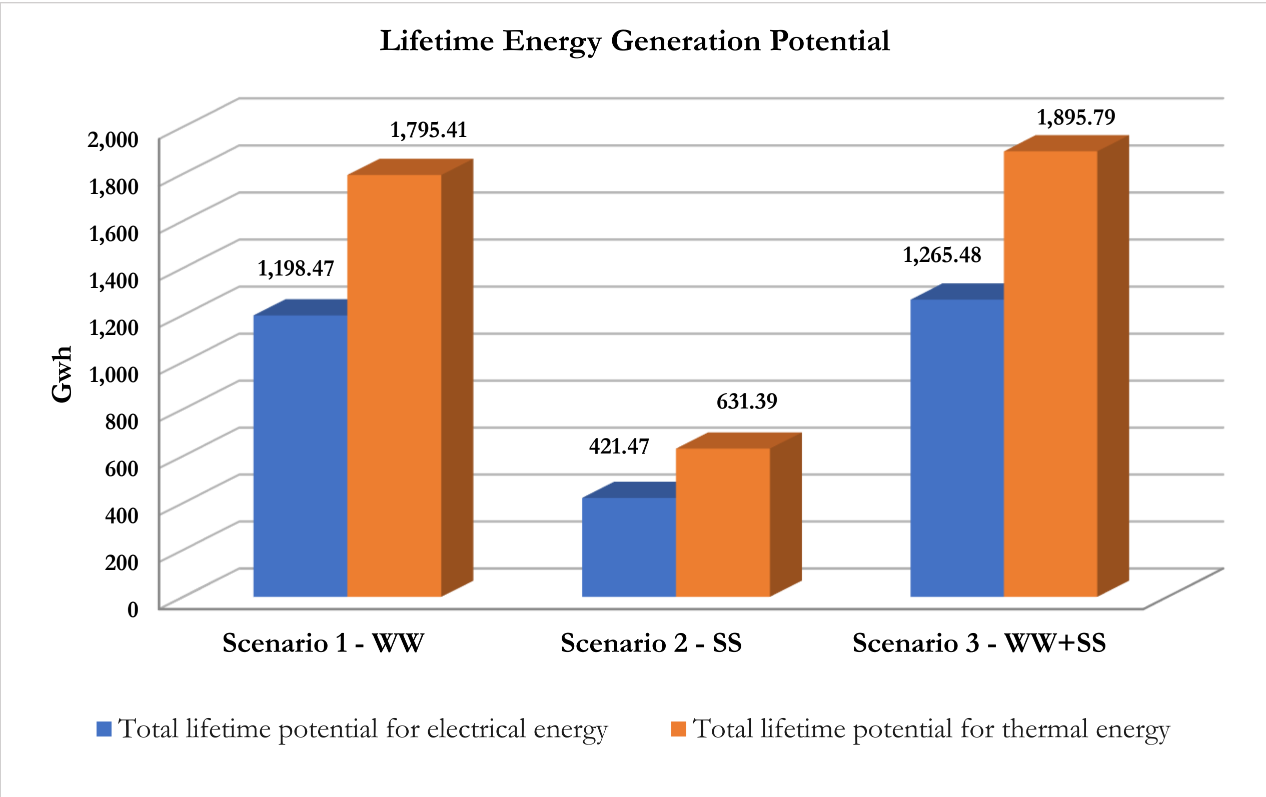

Figure 17 - Total potential for electrical and thermal energy generation from different scenarios

Emissions Reduction Potential

For emissions reduction, only the emissions from production of grid electricity and combustion of fossil fuels were considered replaced by the heat and electricity from biogas. Life cycle emissions from the combustion of biogas in CHP, transportation of fuels, and operation of anaerobic reactors were not considered in the scope of this

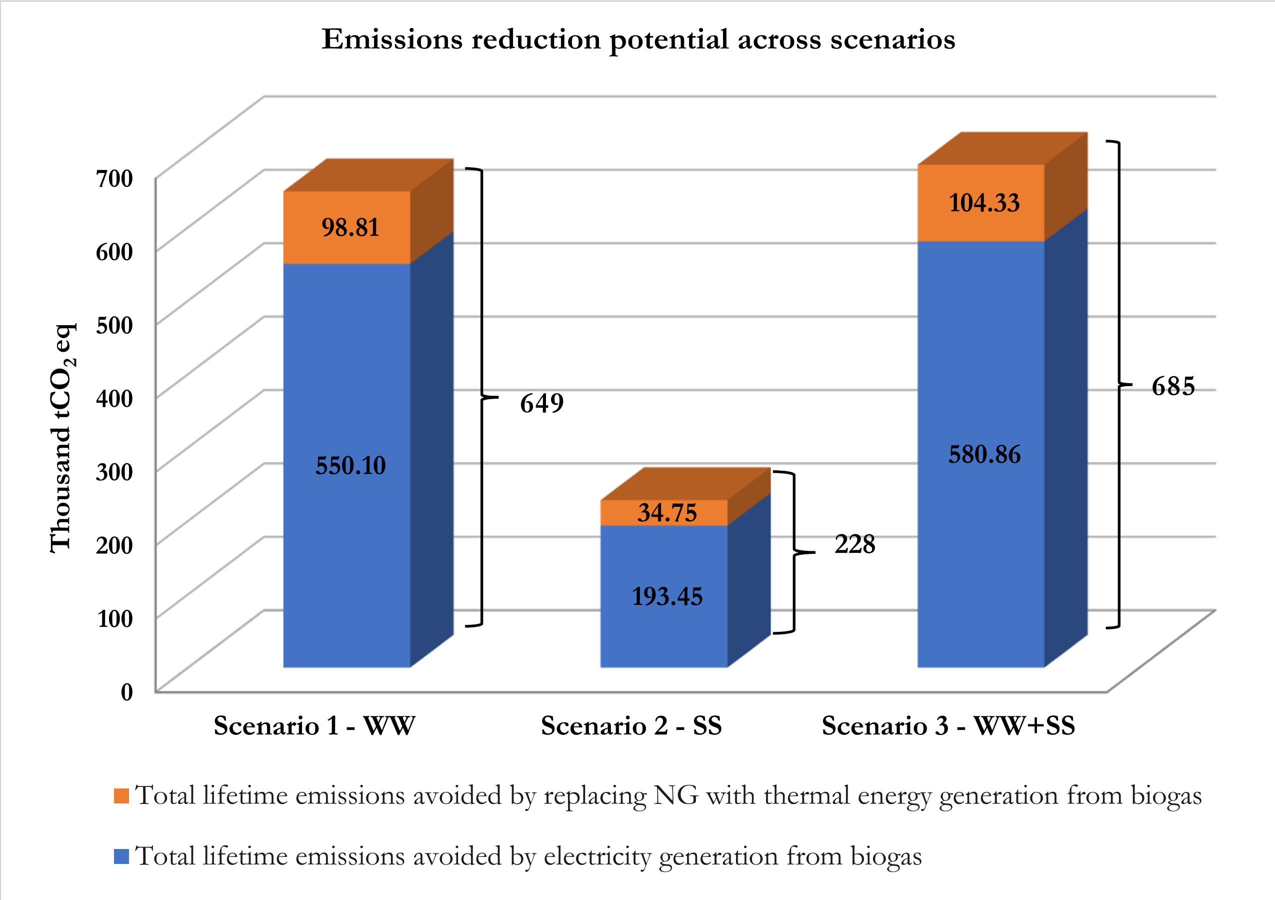

Figure 18 - Total emissions reduction potential of different scenarios

study. A thorough LCA with upstream and downstream emissions would reveal the emissions reduction potential in greater detail. Using the grid electricity emission factor for Georgia, lifetime emissions avoidance potential from electricity generation was 580,850 tCO_2 from combined biogas recovery in scenario 3 – (DWW+SS). Considering emissions reduction from avoiding natural gas usage, the total emissions reduction increases to 685,190 tCO_2 over the project lifetime. Biogas recovery from only sewage sludge in scenario 2 (SS) has the lowest emissions reduction potential, with a total lifetime emissions reduction of 228,200 tCO_2 considering natural gas usage for thermal energy. Emission avoidance potential of different scenarios are further elaborated in the results presented in the graph in Figure 18.

Economic Performance across Scenarios

Considering the economic conditions assumed for calculating the Net Present Value (NPV) and Internal Rate of Return (IRR), it is revealed that biogas recovery from sewage sludge (SS) is not financially feasible, as the NPV over the project lifetime is negative. The greatest feasibility is offered by biogas recovery from domestic wastewater in scenario 1, where the NPV is 7,904,749 EUR over the project lifetime with an IRR of 18%. The combined recovery in scenario 3 (DWW+SS) is also financially feasible with an NPV of 5,408,736 EUR and an IRR of 15%. It should be noted that the financial analysis is performed under certain assumptions and a further sensitivity analysis can reveal the effects of various factors such as discount rate, feed-in tariff, conversion efficiencies, amongst others. Comparing the levelized cost of biogas production, biogas recovery from wastewater (scenario 1 – WW) is the most cost effective, with a lifetime levelized cost of biogas recovery amounting to 0.06 EUR/m^3 of biogas recovered. In comparison, biogas recovery from just sewage sludge (scenario 2 – SS) is twice as expensive, with a levelized cost of 0.12 EUR/m^3 of biogas recovered. In the combined recovery scenario, the levelized cost of biogas recovery is 0.07 EUR/m^3 of biogas. These costs are in line with the renewable power generation costs for 2018 as released by IRENA (IRENA, 2019). Figure 20 and Figure 21 cover the economic performance of the three scenarios.

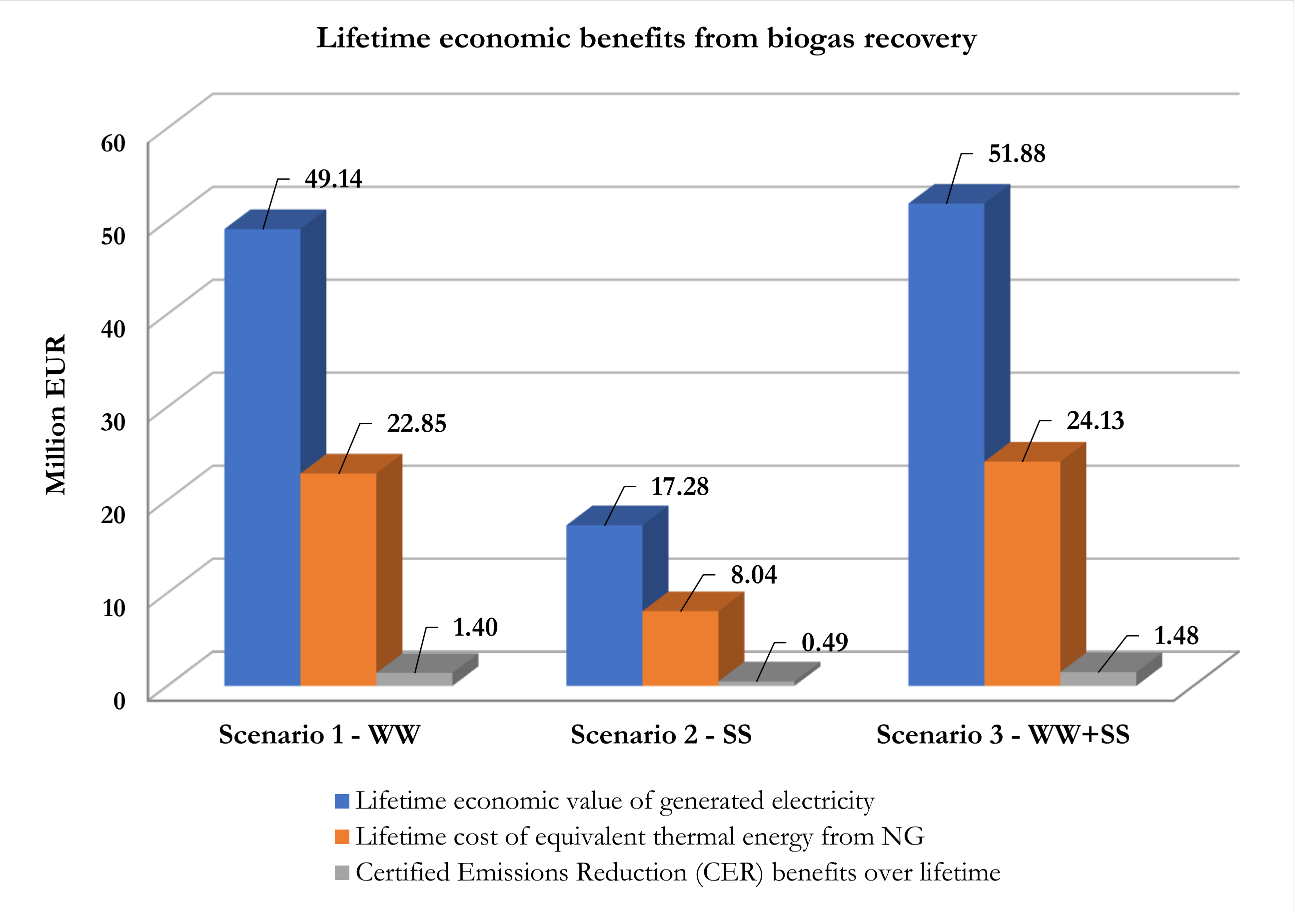

Figure 19 – Economic benefits from different scenarios

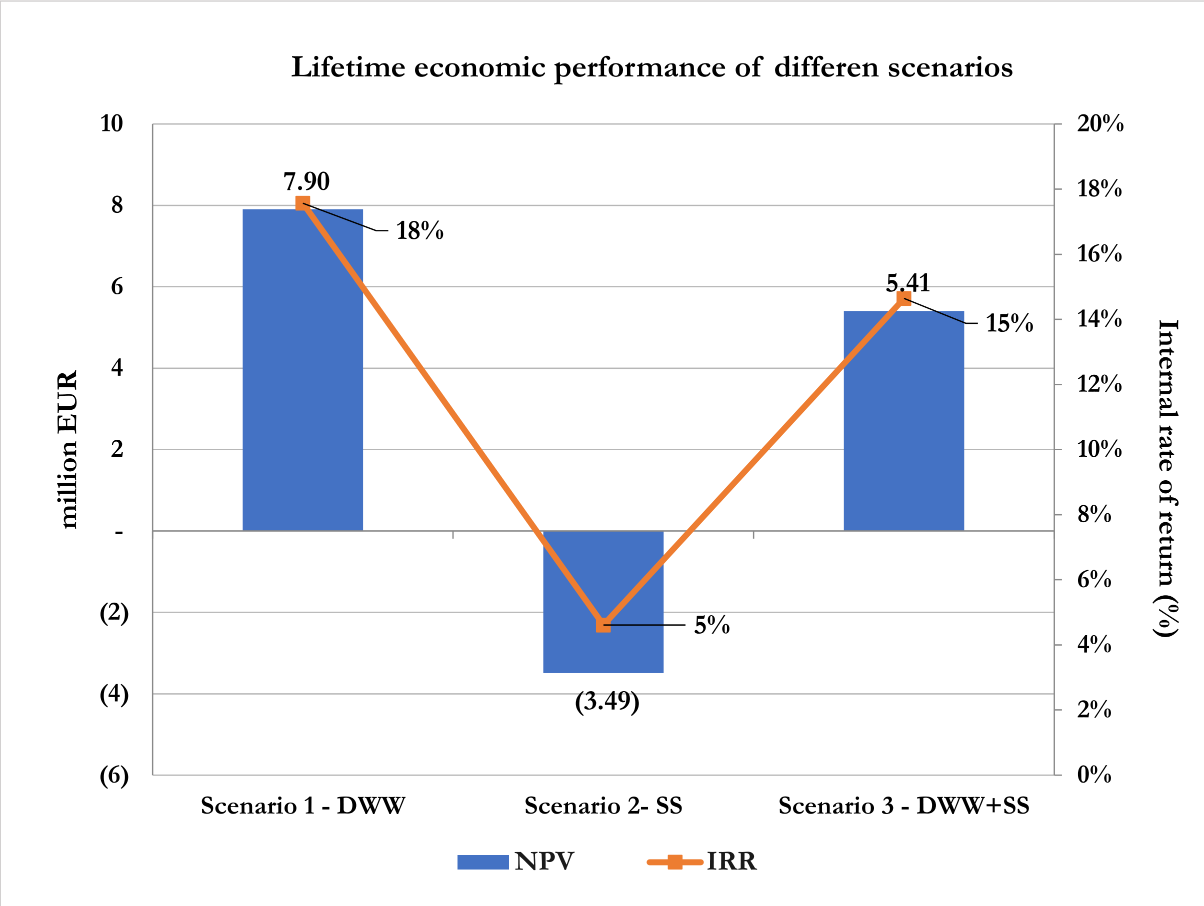

Figure 20 – NPV and IRR performance for different scenarios

7.4.4 Discussion

It is thus evident from the preliminary sustainability indicators that there is a substantial scope for biogas recovery and heat and electricity generation at Gardabani WWTP. While the indicators consider a basic scenario, further analysis with on-site data can reveal further synergies and limitations for biogas recovery. Using the electricity and heat generated in-situ, the WWTP can greatly enhance their energy security and operate in a more sustainable and environmentally responsible manner.

The recovery and utilization of biogas during the sludge treatment in Gardabani WWTP is an interesting prospect. The project provides a substantial means of reducing the GHG emissions from the process cycle of the plant and help the company, the municipality, and the country achieve their sustainability goals for low GHG emissions. It is also an important step towards sustainable management of water resources. The model can be replicated across the country in WWTPs of varying scales, thus enabling the operators to run more efficient, and energy independent treatment plants. While the Sustainable Wastewater Treatment Program (Government of Georgia, 2014) is being planned and implemented in various places across the country, the assessment of techno-economic feasibility of biogas production arrives at an important stage in the planning phase, which can enable the government to build new sustainable WWTPs with integrated biogas recovery right from the beginning. There is also considerable energy savings by using the biogas for electricity production which the plant can utilize for their own consumption. This provides an economic incentive for the plant as well to upgrade their sludge treatment line with anaerobic treatment.

The results from the assessment for Gardabani WWTP were compared with results published in literature for biogas outputs. While most results include the study of systems on laboratory or batch scale with some form of pre-treatment along with biogas recovery, the results from Gardabani are consistent with results from existing literature. The values from different studies have been tabulated in Table 27 for easy comparison. It is evident that there is a considerable scope for improving the biogas output from Gardabani WWTP if suitable pre-treatment or co-digestion strategies are employed.

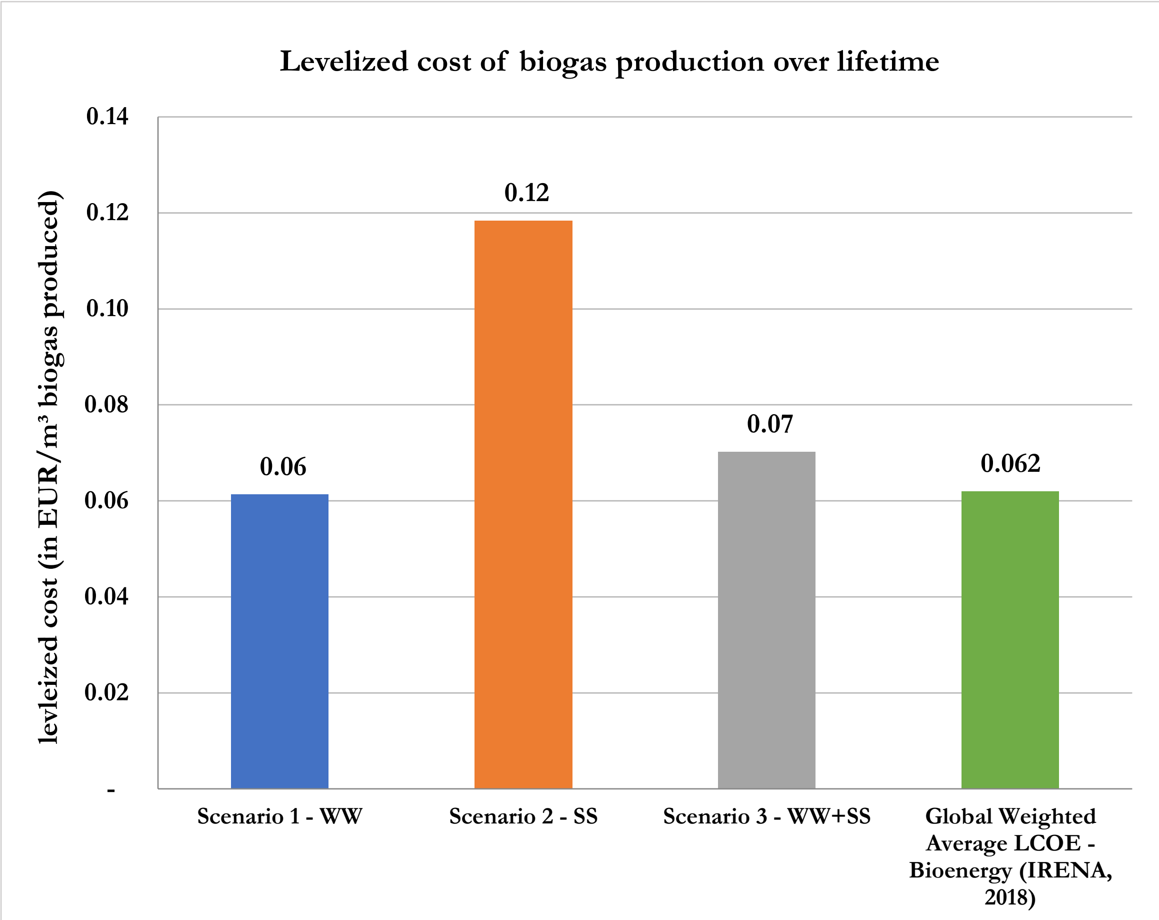

Figure 21 – Comparison of cost of biogas production with IRENA benchmark

Table 27 – Comparison of assessment results with existing literature (compiled by author)

Sr. No.	Configuration	Unit	Results	Remarks	Reference
1	UASB; 740 mg/L influent COD; 60% COD removal efficiency	Nm^3 biogas/kg COD removed	0.303	Results from assessment of Gardabani Wastewater Treatment Plant, Georgia	
		Nm^3 CH_4/kg COD removed	0.182		
		mL biogas/g COD removed	303		
		mL CH_4/g COD removed	182		
2	UASB; 1000 mg/L influent COD; 4-12 L experimental setups; 94-96% COD removal efficiency	Nm^3 biogas/kg COD removed	0.49-0.55	-	(Stazi and Tomei, 2018)
	UASB; 1531 mg/L influent COD; 60,000 L reactor volume; 51% COD removal efficiency	Nm^3 CH_4/kg COD removed	0.25	-	
3	CSTR Reactor (WAS); 22 L batch scale setup; 35°C; 37% Hydrochloric acid pretreatment - 1 day;	mL CH_4/g COD removed	124.5	-	(Raheem et al., 2018)
4	Anaerobic digester; 200 mg/L COD conc. in the supernatant; VSS removal efficiency; 45%;	NL CH_4/g $COD_{degraded}$	0.35	Main assumption for mass balance calculations	(Bertanza et al., 2018)
5	Mesophilic AnMBR; Influent COD 500 mg/L	mL CH_4/g COD removed	300	With combined heat pump and forward osmosis (FO)	(Gu et al., 2017a)

8 Discussions and Conclusion

8.1 Knowledge gaps

The focus on circular economy and sustainable development is slowly bringing about a paradigm shift in the wastewater treatment sector. Wastewater Treatment Plants (WWTPs) are now being viewed and developed as Wastewater Resource Recovery Facilities (WRRFs). While this transition is imperative for sustainable management of our urban water resources, there are still major gaps in the research and knowledge base required to bring about the transition on a global scale.

In terms of the technological processes for biogas recovery from wastewater and sludge, there is still a scope for further optimization of the processes. Several issues such as long start-up times, lower organic matter removal, high concentration of effluent pathogens, nutrients, and suspended solids (SS) make it difficult to achieve water quality standards with existing anaerobic digestion technologies. There is a need for further research into optimization of process efficiency to achieve better solids retention, lower starting times, and improve methane production. Studying co-digestion of wastewater and sludge with organic substrates, and testing on industrial-scale pilot projects can help further increase the methane production potential in WRRFs. There is a need for research into technologies that improve on the synergy between treated effluent quality and biogas production.

Further research needs are observed in the sustainability assessments of biogas recovery systems. Quantitative economic, environmental, and social assessments can help promote further implementation of full-scale biogas recovery systems in WRRFs by providing data-driven insights into the costs and benefits of implementing biogas recovery. Future studies can focus on improving the economic viability of biogas recovery systems by studying combinations of pre-treatment, anaerobic digestion reactor technologies, and end uses of recovered products. Context-based studies for contributions to the SDGs can help WRRFs and municipalities promote their sustainability endeavours and gain better social acceptance from the local populations.

While there have been studies that examined the potential for anaerobic digestion of wastewater and sewage sludge, most of the studies used assumptions and data from similar plants to simulate results. (Bachmann, 2015) suggests that monitoring systems in WWTPs can be a crucial step in sustainable biogas production from wastewater and sludge. WRRFs should maintain detailed reports of process evaluations and highlight good and unsatisfactory performances, as well as avenues for further optimization. Awareness about the limitations and advantages of each stage of the treatment process can help identify possibilities for improvement and can be used to upgrade old processes with newer, more efficient ones.

On a regional scale, country level data for biogas recovery wastewater is scarce as well. A few countries such as USA, Germany, Italy, Sweden have reliable data on biogas production, but there is a marked absence in developing countries of systematic monitoring of energy generation in wastewater treatment facilities. State-wide monitoring and reporting of biogas generation from WRRFs can help to address policy issues, and design better economic policy instruments to promote further adoption of biogas recovery systems in WRRFs. There is also a need for better legislations and incentives that particularly target bio-energy and sustainable wastewater management, making it easier for WRRFs to implement biogas recovery in their facilities.

8.2 Policy discussions

Biogas recovery from wastewater and sludge is linked to the water-energy nexus, and is dependent on policies, regulations, legislations, and incentives in the water, energy, and environmental sectors. Regulations targeting climate change mitigation, energy security, improved environmental quality can positively or negatively affect the further adoption of the biogas recovery concept in WWTPs. While the policies may not be explicitly designed for AD or biogas recovery from wastewater, most environmental and sustainable development policies have been found to have a positive reinforcement on the adoption of biogas-based energy recovery from anaerobic digestion. It has been noted that countries with stringent energy, environmental, and water based legislation have a higher prevalence of anaerobic digestion technologies (Vasco-Correa et al., 2017).

The advantages of energy recovery are multi-dimensional and inter-generational, resulting in reduced consumption of energy, reduced emissions, availability of further resources, and establishment of new value chains that can benefit multiple stakeholders. Thus, it is imperative that sustainable policy instrument design should be developed with a long-range planning perspective, exceeding the short-term election cycles and operating independently of electoral objectives. The water quality and environmental performance standards should be developed such that they are considerate of the needs of future generations.

In this section, the most effective policies, legislations, and incentives for promoting biogas recovery have been discussed. The studied policies can be categorized as follows: 1) Renewable energy policies; 2) Comprehensive environmental regulations; 3) Waste management policies.

8.2.1 Renewable energy policies

Biogas and biomethane recovered during AD in WWTPs is a renewable source of energy. It can be mixed and interchanged with natural gas and can thus be used with existing natural gas-based systems for heat/electricity generation or transportation. Thus, policies promoting renewable energy sources and fuels can positively stimulate the production and adoption of further biogas-based energy. **Renewable energy targets** requiring a certain proportion of renewable energy in the energy mix within a specific period are a common policy measure being used across the world for promoting renewable energy usage. Biogas recovery from wastewater and sludge feeds directly into renewable energy targets and can help a country generate a considerable amount of renewable natural gas from their organic resources. For example, Germany has been able to promote anaerobic digestion by passing the Biofuels Quota Act (2007), which mandates the sale of a minimum percentage of biofuels in the open market. Many countries in the EU, like Sweden, have specific Renewable Energy Targets for biomethane and biogas production (Swedish Gas Association, 2018; Vasco-Correa et al., 2017)

Greenhouse Gas emission reduction targets can also help promote further biogas recovery in wastewater treatment facilities. Biogas generation has the potential to avoid the emission of methane to the atmosphere and can help achieve significant emission reductions for the plants, and thus the country. Further downstream emissions can be reduced by using carbon neutral biogas instead of fossil fuels or grid electricity for heating and electricity requirements. Thus, stringent emission reduction targets, along with suitable incentives for bioenergy can help in the further adoption of biogas recovery from wastewater and other organic sources (Edwards et al., 2015). For example, the EU utilizes the Renewable Energy Directive (RED) as a framework for member countries to help achieve CO_2 emission reduction targets. Bioenergy from anaerobic digestion is promoted within the RED due to its potential for emissions reduction and significant environmental benefits (European Commission, 2011). Countries can improve the adoption of biogas recovery from such targeted legislations for promotion of bioenergy.

8.2.2 Environmental regulations

Utilizing anaerobic digestion for wastewater and sludge treatment not only helps achieve energy recovery through biogas, but also has significant environmental advantages in the form of improved effluent quality, reduced GHG emissions, nutrients and odours management. Environmental policies that focus on air emissions, water quality norms, and nutrient management can promote the adoption of anaerobic digestion in WWTPs. Plant owners are increasingly being brought under stringent environmental control in developing countries with new legislations, and implementing biogas recovery and anaerobic digestion can help them achieve their environmental targets (Asian Development Bank, 2010; Vasco-Correa et al., 2017)

Water sector-specific environmental regulations have long been implemented in the EU by the Council Directive 91/271/EEC on urban wastewater treatment in 1991, and Sewage Sludge Directive 86/278/EEC in 1986. Such targeted legislations can help promote the sustainable treatment of sludge and wastewater, recovery of resources, and the beneficial reuse of the resources recovered during such treatment (Kiselev et al., 2019). Developing countries can model their sustainable water treatment regulations based on these long-standing regulations in the EU and achieve greater environmental benefits.

The implementation of integrated environmental protection systems, as suggested by Lettinga (Hulshoff Pol et al., 2008), present a further useful approach for conciliating wastewater treatment and the recovery of resources from its by-products. It is especially applicable for developing countries, where grave environmental problems, lack of resources, and energy scarcity pose serious threats to the quality of life. Biogas recovery, and by extension, the whole concept of integrated anaerobic digestion in wastewater treatment plants present an excellent opportunity for addressing these problems. Energy recovery, generating cleaner effluents, and a useful by-product in the form of treated and stabilized sludge can help improve energy access, agricultural output and address food production issues (Lemos Chernicharo, 2007). An integrated anaerobic digestion process is shown below, as described by Lettinga Associates Foundation (Hulshoff Pol et al., 2008).

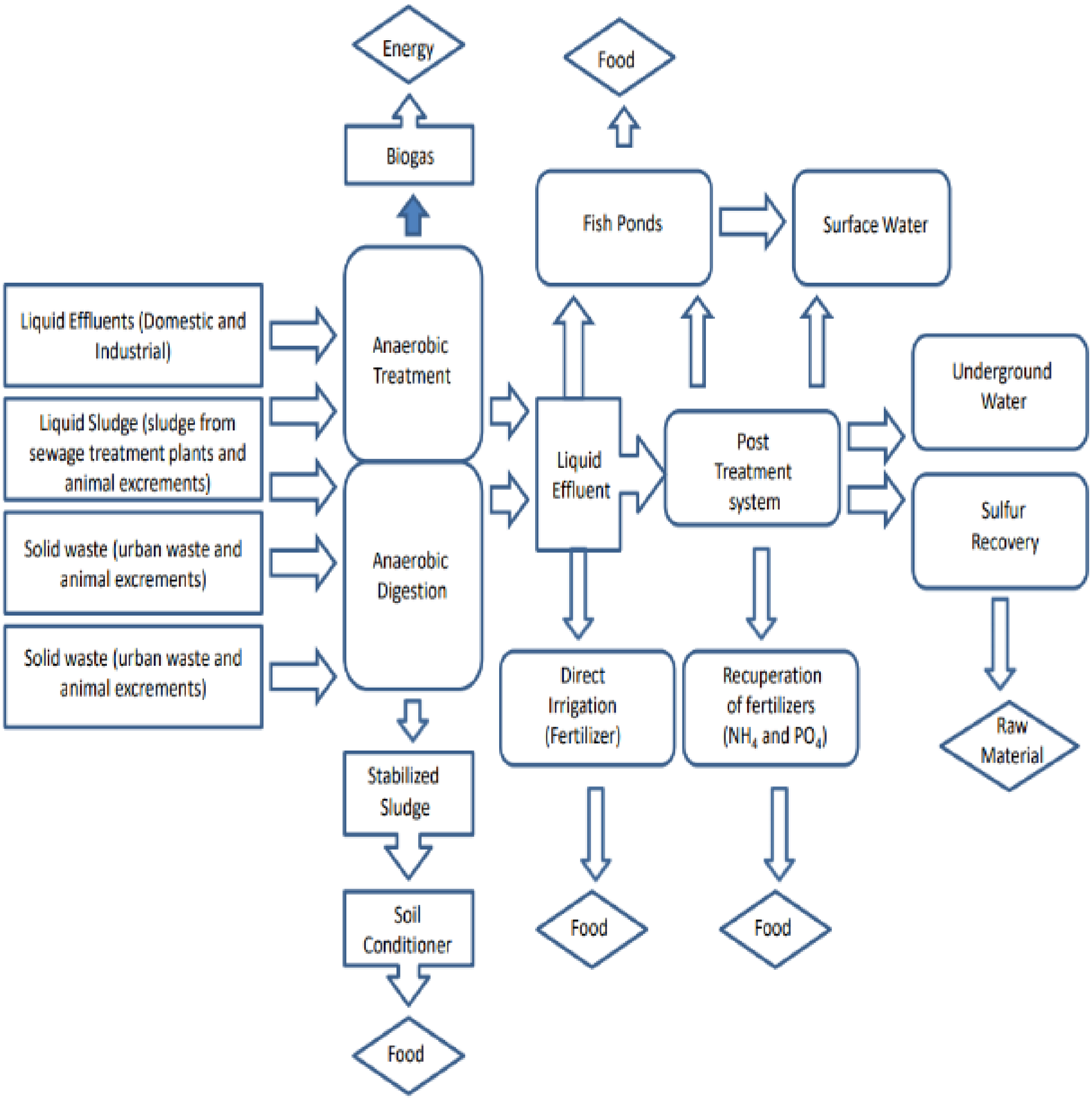

Figure 22 - AD as integrated technology for sewage treatment and by-product recovery. Adapted from (Hulshoff Pol et al., 2008)

8.2.3 Waste management policies

Sludge management and disposal is a major cause of concern for wastewater treatment plants. With growing sludge production and stricter disposal regulations, it is becoming imperative for plant operators to manage their sludge waste sustainably. Anaerobic digestion can help achieve sustainable sludge management as AD helps significantly reduce sludge volume and pathogen load (Andreoli et al., 2007; Tchobanoglous et al., 2014). Stringent sludge disposal regulations can thus help make anaerobic digestion and biogas recovery an attractive and feasible technology for WWTP owners looking to achieve sustainable management of their sludge wastes. Further, landfill disposal regulations have also been found to have a positive correlation with higher adoption of anaerobic digestion technologies (Edwards et al., 2015). Disposal of OFMSW in landfills has severe environmental impacts, and co-digestion in wastewater treatment plants offers an attractive alternative of achieving several environmental benefits at once. WWTPs can generate further revenues from tipping fees for additional waste streams, and benefit from novel policies such as the

Landfill Allowance Trading Scheme introduced in the UK, which allows regions with low diversion of organic waste from landfills to purchase allowances from regions with higher landfill diversion efficiencies (Edwards et al., 2015) (Hulshoff Pol et al., 2008)

8.2.4 Incentives

Anaerobic digestion is the key technology for biogas recovery from organic substrates, including wastewater and sewage sludge. While there have been significant advances in the field of anaerobic digestion, there are still various limitations towards widespread adoption of biogas generation across the world. Financial challenges like high capital costs, high operations and maintenance costs make it difficult for enterprises to feasibly adopt such technologies. To promote biogas recovery in WWTPs, several financial incentive programs can be useful, which can help offset portions of the initial investment cost, or provide alternate revenue streams that can make AD competitive against traditional energy production technologies (Edwards et al., 2015; Vasco-Correa et al., 2017). Some of these incentives are discussed briefly below:

1. **Feed-in Tariff:** Energy generation through AD can be prioritized by providing higher FiT rates for bioenergy as compared to other renewable energy sources. For example, Germany provides bonuses for using feedstocks such as animal manure, plant biomass, or crop biomass for producing biogas from AD, along with a higher feed-in tariff for electricity generated from biogas (Edwards et al., 2015).
2. **Carbon Reduction/Trading Credits:** Biogas recovery from wastewater can qualify for carbon credits as it avoids methane emissions and reduces electricity generation from fossil fuels. Thus, WWTPs can benefit from carbon credit and trading schemes that provide revenues for managing GHG emissions. For example, California's Low Carbon Fuel Standard makes AD projects in the state eligible for carbon credits (Vasco-Correa et al., 2017).
3. **Tax Exemptions:** Tax exemptions on renewable energy sources can be applicable to biogas recovery systems as well. They have been found to significantly improve growth of AD systems in countries with such tax benefits (Global Methane Initiative, 2014). Examples include the Renewable Electricity Production Tax Credit in the USA for technologies that utilize biomass other than dedicated energy crops, and the Climate Change Levy tax exemption given to AD facilities (Global Methane Initiative, 2014)
4. **Renewable Energy/Transportation Fuel Credits:** Renewable energy credits aim to monetize the environmental benefits of generating and using renewable energy, and biogas recovery systems can be eligible for such credits (Vasco-Correa et al., 2017). Renewable transport fuel credits can also help promote adoption of biogas recovery in WWTPs, as the plants can become producers of renewable natural gas and generate revenue from the sale of the gas and be eligible for renewable transportation fuel credits. Germany's "Initiative for Natural Gas-based Mobility" and USA's Renewable Fuel Standard (RFS2) are examples of such transportation fuel credits (Global Methane Initiative, 2014; Vasco-Correa et al., 2017)

5. **Nutrient Load Reduction Credits:** While such credit schemes are not widely used, they can be a powerful tool for adoption of AD and biogas technologies. Such credits schemes focus on reducing the nutrient load introduced to water bodies from waste streams. WWTPs can greatly benefit from such credits by implementing AD technologies and achieving nutrient load reduction in the effluents while recovering biogas. The Chesapeake Bay Nutrient Credit Trading program in the U.S. is a pioneering example of such a trading program (Global Methane Initiative, 2014).

8.3 Market drivers

Biological waste-based resource recovery is going to be an important tool in the forthcoming transition to clean energy. Shifting towards a bio-based economy has immense potential to solve major problems in waste management, greenhouse gas mitigation, and can help end our dependence on fossil fuels. With concerted efforts in research and development of technologies and processes, powerful and effective legislation, incentives, and policies, the perspective towards wastewater can change and the true energy and resource recovery potential of this valuable waste stream can be realized.

Market drivers are factors that help create the market and ecosphere for the development and adoption of new technologies, services, or products to satisfy the evolving needs of the market (Kalogo and Monteith, 2012). Several market drivers can be identified that will act as key factors driving the need for energy and resource recovery from wastewater and sludge. Four major drivers have been identified and discussed below:

1. **Environmental / sustainability concerns**

   Wastewater and sludge treatment represent a significant energy consumption for countries. (Shen et al., 2015) state that municipal wastewater treatment consumed 3-4% of USA's national electrical demand, and added 21 million metric tons of GHG emissions annually. With increasing focus on sustainability, energy efficiency, and the environmental impact of human activity, it is going to become imperative for WWTPs to improve on their sustainability performance and become further energy independent while reducing the carbon footprint of water and sludge treatment. On an industry-wide scale, greater renewable energy recovery will enable large-scale reduction of GHG emissions. Thus, there is a strong incentive for manufacturers and plant operators to focus on energy recovery in form of biogas and other resources as the demand for environmentally friendly water treatment will only increase with time (Kalogo and Monteith, 2012).

   Anaerobic digestion is well positioned as a technology that can help achieve greater sustainability and energy independence for wastewater and sludge treatment plants. With innovative processes such as AnMBR, high-quality effluents can be produced that cause negligible harm to water resources, improving the effectiveness of the treatment process. Biogas recovery is an ideal energy recovery process that allows the production of heat and electricity from renewable biogas. These can then be used in a variety of methods, as discussed in earlier chapters, and help WWTPs become net energy producers.

2. **Energy cost and type**

Energy is a key operational requirement for wastewater treatment plants, with 25% of O&M costs in WWTPs being used for energy-based expenses (Kalogo and Monteith, 2012). With rising energy prices and stricter emission norms, it will become increasingly difficult for plants to manage their operational costs. This necessitates the selection and adoption of the most cost-effective and efficient energy recovery strategy for the plant operators. There have been several cases where rising energy costs compelled WWTPs to further depend on energy recovery (Maktabifard et al., 2018; Stazi and Tomei, 2018; WERF, 2015). There is considerable research showing that wastewater and sludge contain a lot more energy than is needed for their treatment (Kalogo and Monteith, 2012). This suggests that there is a scope for development of new technologies, and/or optimizing existing technologies, that will enable greater energy recovery.

There is an important distinction between energy recovered as heat or electricity, as both types of energy are required for wastewater treatment. Biogas recovery from AD and further energy conversion using CHP engines is a cost-effective and well-tested method to recover high quality heat and energy that can be directly used by the treatment plant. Further improvements in CHP efficiencies or using fuel cells will make the process more feasible for WWTPs, enabling the transition to lower costs and improved sustainability.

3. **Regulation / legislation**

National policies and regulations can play an important role in stimulating sustainable development, and increasing the focus on energy efficiency. Well-planned legislations can help overcome economic barriers and create the stimulus needed for the development of new markets. Such regulation can be witnessed in Europe in terms of the Water Framework Directive (WFD) (Metz and Ingold, 2014), and on a national level in Sweden, where resource recovery from wastewater and sewage sludge has been mandated by law, and biogas recovery from organic wastes is promoted by the state, creating a thriving biogas market (Swedish Gas Association, 2018).

With growing environmental concerns and focus on sustainability, necessary regulations and legislation will drive the need for further energy efficiency and energy recovery in wastewater treatment. Further, stringent emission norms will require WWTPs to control their GHG emissions generated from usage of electricity, fossil fuel usage, and methane emissions from sludge. Biogas recovery can aid WWTPs in complying with stricter energy and emission regulations. Conversely, necessary regulation for sustainable development and energy usage will promote the adoption of biogas recovery in both large-scale and small-scale WWTPs.

8.4 Suitable technological options and future developments

8.4.1 Biorefinery concept

The importance and scope of biogas recovery from wastewater and sewage sludge has been examined in detail in the previous sections of this thesis. It is evident from existing research and data trends that resource recovery from wastewater in the form of energy, nutrients, and materials will become increasingly necessary to meet sustainability requirements in the future. Biogas, among other valuable products can be viably recovered from wastewater treatment plants, shifting the focus of WWTPs as waste processing facilities to being considered as Wastewater Resource Recovery Facilities (WRRFs) (Fernández-Arévalo et al., 2017). Several concepts for sustainable development of wastewater resource recovery facilities have been discussed.

The biorefinery concept envisages the development of environmental biorefineries, which can be defined as "facilities that convert bio-waste inputs into energy, fuel, chemicals, and materials". Akin to petrochemical refineries, these biorefineries will be able to produce a range of principal products and services that can be instrumental in replacing some of our petroleum-based energy and material requirements through the recovery of bio-energy, biofuels, minerals, bioplastics etc. Through technology development and further research into process integration, the refineries can expand the range of products they can recover. The variation in the incoming streams of bio-waste and their complex make-up pose a significant technical challenge, but this variety can be utilized as an advantage to recover multiple end products (Amulya et al., 2016). WWTPs are well-suited to be developed as bio-refineries with a steady input of biological substrate in the form of wastewater. Figure 23 shows a schematic of a biorefinery process.

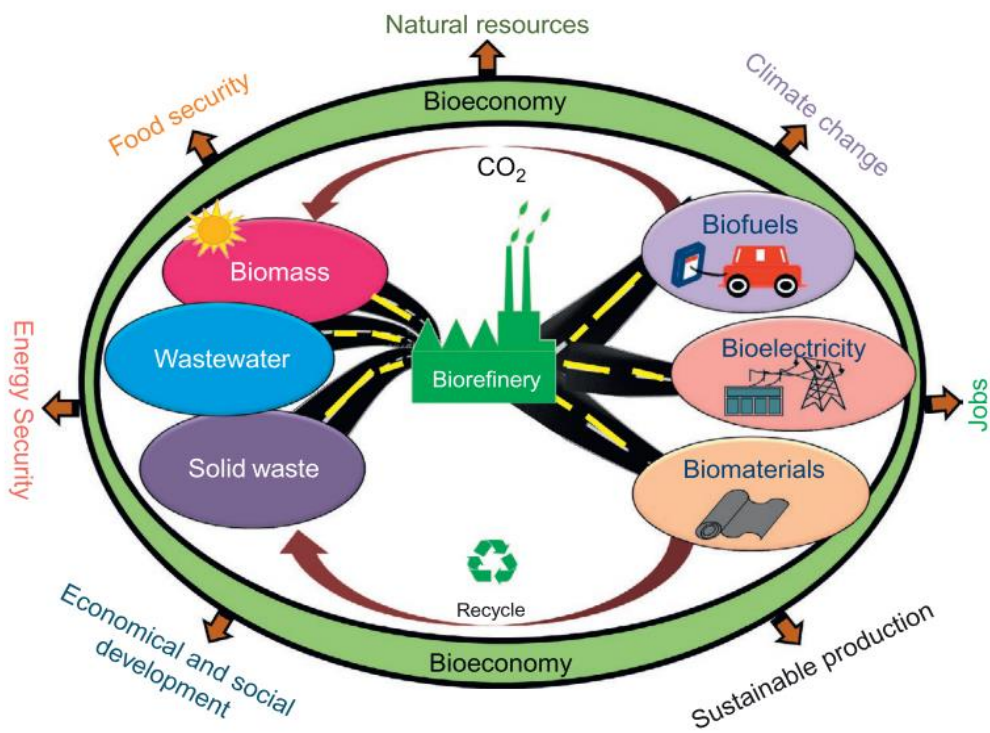

Figure 23 – Biogas refinery concept. Adapted from (Amulya et al., 2016)

The opportunity to co-digest other organic waste streams such OFMSW or agricultural waste can aid in improving the process efficiency for anaerobic digestion (Bachmann, 2015). Such bio-refineries can produce high-value, low volume products such as biochemicals, building materials, and drop-in fuels. Other low-value, high-volume products can include renewable natural gas, electricity, heat, organic fertilizer. Such resource recovery can help improve the sustainability and overall economics of the WRRF processes, facilitate better utilization of the AD technologies, and improve energy security for the plant and the region in general (Vasco-Correa et al., 2017).

8.4.2 Solar energy integration

Integrating solar energy into the WWTPs along with biogas recovery can aid in further energy independence for the plants. (Maktabifard et al., 2018) report several successful applications of solar PV systems in WWTPs. Solar PV arrays can be installed on top of overflow ponds and clarifiers, with the added benefits of cooling due to water, and prevention of algal growth due to shade from the panels. A WWTP in Australia employing similar installation of solar farms on an overflow pond is able to produce 180,000 kWh of electricity in a year, covering 12% of the plant's total energy consumption (Harper, 2017). Another useful application of solar energy can be for sludge drying post anaerobic digestion. The advantages of this application are noted by (Singh and Kansal, 2018), highlighting that the average electrical energy intensity for WWTPs in India (0.14 KWh/m^3) is much lower than that in the UK (0.46 KWh/m^3) due to the use of solar energy in Indian WWTPs for sludge drying.

8.4.3 Anaerobic membrane bioreactors

The anaerobic membrane bioreactors (AnMBR) present the new frontier of technological development for large-scale anaerobic digestion processes. The development and further application of AnMBR will help expand the possible applications of AD to treat new substrates, which may include pharmaceutical wastes, municipal sludge, petrochemical, and winery wastes (Dereli et al., 2012). The major advantage of AnMBR over conventional high-rate AD systems such as UASB and EGSB is the almost complete retention of solid particles. Due to this, AnMBRs can produce high-quality effluents with minimal pathogens and solids, while retaining the microbial populations inside the bioreactor. The retention of microbial communities is highly beneficial as it results in higher treatment efficiency, enabling the treatment of heavily polluted wastewaters from different industries (Puyol et al., 2017)

While AnMBRs are highly efficient at COD, SS, and soluble substrate removal, they have several major limitations in terms of cost and process optimization. One of the greatest issues is membrane fouling, which can occur due to the accumulation of particles, colloidal matter, and bacteria on the membrane surface (Bajpai, 2017). This reduces the filtration efficiency, entails frequent cleaning, and reduces the life of the membrane. Techniques used to mitigate fouling include gas scourging, which uses the generated biogas pumped at high velocities to scour the membrane surface, reducing the accumulation of matter. However, the energy requirements for scourging are in the range of 0.6-1.6 kWh/m^3 (Stazi and Tomei, 2018) and thus make the process highly energy intensive. Another major limitation is the high cost of membranes, which leads to higher replacement and maintenance costs (Lin et al., 2013).

When evaluating the benefits of AnMBRs, (Mccarty et al., 2011) concluded that a domestic wastewater treatment plant could double their energy production by employing a full anaerobic treatment of sewage using AnMBR. The energy production can even exceed the WWTPs energy demands, making it a net energy producer. Although full anaerobic treatment of municipal wastewater and sewage has the most potential for energy recovery, it may not be feasible to upgrade existing aerobic-anaerobic systems to complete anaerobic facilities. Thus, such systems may be more suitable for new WWTPs being built (Puyol et al., 2017).

8.4.4 Phosphorous recovery

Municipal wastewater is being increasingly considered as a viable source for recovering phosphorous, as elemental phosphorous is a non-renewable mineral and will become increasingly expensive to mine (Tyagi and Lo, 2016). Phosphorous recovery from wastewater and sludge will eventually become necessary, which can serve as a valuable revenue stream for WWTPs. (Kalogo and Monteith, 2012) state that phosphorous recovery is the most valuable use of sewage sludge, not just from sustainability perspectives, but also because of its economic value. The commercial value for 1kg of P as a fertilizer is approximately US$ 2.6, with the dry solid content of waste-activated sludge containing approximately 1kg of P/inhabitant.year (Kroiss, 2004). While currently the P recovered from wastewater costs 1.6 to 3 times more than commercial P, the process can become more cost-efficient as new technologies are developed and the cost of commercial P drives higher due to limited supply (Raheem et al., 2018)

An interesting technological concept is the simultaneous recovery of phosphorous and energy, which can be highly cost-effective for the WWTP. Two such processes have been developed in Sweden:

The first one is a Two-Stage Acid-Base Leaching Concept developed at KTH, Stockholm by (Levlin and Hultman, 2004). The concept employs an activated sludge process with biological nutrient removal. The sludge from this process is then subjected to anaerobic digestion, producing biogas and releasing phosphates in the supernatant from the digestion. After separation of the digested sludge, the supernatant can be used to recover phosphorous in the form of struvite (magnesium ammonium phosphate), or phosphoric acid (Levlin and Hultman, 1998). Another pathway to recover energy and phosphorous from the same process can include the incineration of digested sludge for energy recovery, and the subsequent leaching of the ash with acid and base to recover phosphorous. Leaching sludge incineration ash with acid gave a 75 – 90% leached phosphorous at a concentration of 1 M, whereas alkaline leaching gave a 50 – 70% recovery of leached phosphorous at 1 M concentration (Levlin and Hultman, 2004).

The major issue with P recovery currently is the high cost compared to commercial P. However, with the maturity of technologies to commercial levels, and the focus on sustainable all-inclusive management of wastewater and sludge resources, P recovery is poised to become a norm in WWTPs of the future. Switzerland has already introduced regulations that will make phosphorous recovery from sewage sludge a mandatory requirement (Bachmann, 2015).

8.4.5 Bio-hydrogen recovery

Hydrogen is being considered as an important energy carrier of the future as its combustion does not produce any CO_2 and has a relatively high energy density. The current technologies for H_2 production – natural gas steam reforming (50% of global H_2 production), oil reforming (30%), coal gasification (18%) – are highly dependent fossil fuels and are energy intensive (Roy and Das, 2016). This makes the process have a large carbon footprint and makes it environmentally unsustainable. There is a need for sustainable processes for hydrogen production that are cost-effective and environmentally friendly (Puyol et al., 2017).

Dark fermentation (DF) is a biological process for hydrogen production that has been recently explored as a sustainable alternative to the fossil fuel based methods used previously. A major advantage of DF is the ability to utilize the organic matter in wastewater as feedstock for the process, thereby achieving energy recovery and water treatment objectives simultaneously (Han and Shin, 2004). DF is a sub-process of the full anaerobic digestion (AD) process, where carbohydrate rich organic substrates are degraded into simple organic compounds, majorly as volatile fatty acids by anaerobic and other facultative bacteria. There is a simultaneous production of hydrogen that can be then recovered and used further (Puyol et al., 2017).

DF can be integrated into existing AD processes with reasonable modifications, to create a two-phase anaerobic process that results in the production of a H_2 rich biogas (also called biohythane) (Cavinato et al., 2011). Research shows that the high hydrogen content in biogas improves the power output and thermal efficiency of the blend, while reducing the emissions of harmful pollutants on combustion (Porpatham et al., 2007). Thus, the simultaneous recovery of hydrogen and biogas from existing AD processes presents a feasible opportunity to improve upon the energy recovery from wastewater. The higher investment costs and complexity pose challenges to the further adoption of two-phase systems, which were estimated to be around 7% of current AD infrastructure in Europe treating municipal solid waste (Puyol et al., 2017).

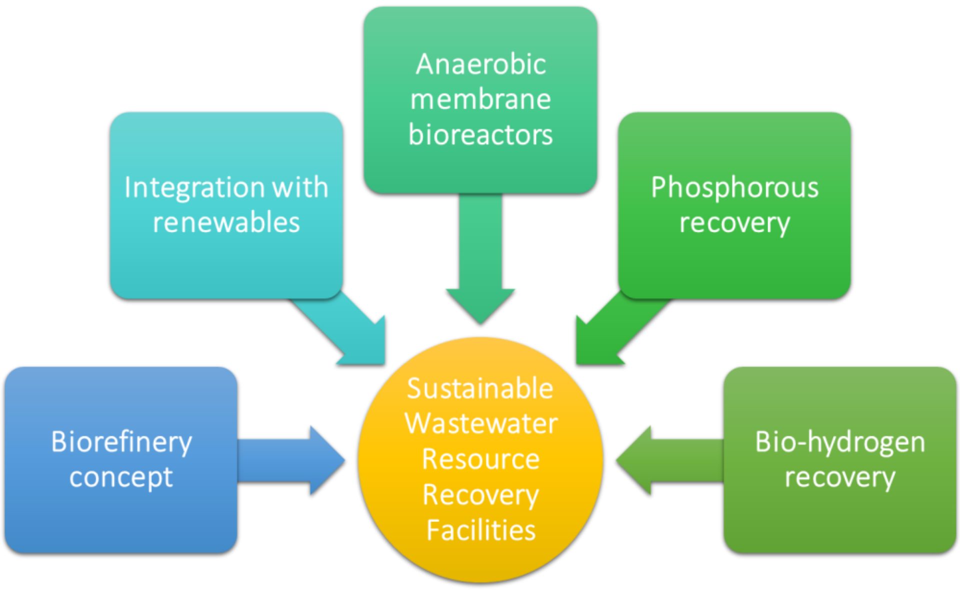

Figure 24 – Future of Sustainable Wastewater Resource Recovery Facilities (WRRFs)

8.5 Conclusion

Resource recovery from wastewater treatment offers a multitude of benefits for sustainable development, circular economy, and renewable energy. While the potential benefits of recovering energy, nutrients, and organic matter from wastewater are well known, there are several knowledge and implementation gaps that prevent the full realization of this potential. This research project aimed to work in that research gap and provide a comprehensive qualitative and quantitative review of energy and resource recovery from WWTPs.

This thesis explored the impact and potential of resource recovery from all three perspectives. The qualitative analysis for mapping the contributions to SDGs helped reveal the cross-sectoral and multi-disciplinary benefits of resource recovery from wastewater facilities. Benefits from different resource such as energy, can be accrued to various goals in the biosphere, social, and economic tiers of the SDGs. The contribution matrices elucidated the cross-linkages between several goals, and how one advantage of resource recovery can contribute to several of the SDGs. The benefits flowed both up, and down the wedding cake model of the SDGs used for analysis. It is important to keep these multi-faceted contributions in mind when designing adequate sustainable resource recovery systems for every local context. The needs and expectations from one project might be different from another. The guiding principles for design of sustainable resource recovery systems can help serve as the framework to ensure all dimensions of sustainability are considered.

The thesis then dived deeper into the technical and quantitative analysis for energy recovery using anaerobic digestion as a tool for achieving sustainable, energy-efficient urban wastewater resource management. The importance of anaerobic treatment of domestic wastewater and sewage sludge is apparent from the multi-fold benefits of renewable energy generation, greenhouse gas emissions reduction, nutrient load management in effluent wastewater, and closing of nutrient and energy loops in a circular economy framework.

The sustainable development of future wastewater resource recovery facilities will require comprehensive sustainability assessment for the environmental, economic, and social impacts. The various methodologies for sustainability assessment of energy recovery systems were discussed to understand how the multiple dimensions of sustainability of are integrated in assessments. Based on the current trends in evaluation methodologies, a set of preliminary sustainability indicators were defined that fairly represented all benefits of energy recovery in the form of biogas. These indicators were chosen for their simplicity in quantification, and relevant information that could be used as go no-go indicators for decision making.

The indicators were then used in a case study for assessing the biogas generation potential for the Gardabani WWTP serving Tbilisi. Data was sourced from existing research and Georgia-specific datasets. It is evident from the indicator data that biogas recovery and heat and electricity generation. The case study results reveal a significant potential to improve the energy security and environmental sustainability of the WWTP, and further analysis using cost-benefit analysis and LCA will be beneficial to fully understand the potential for energy recovery.

Lastly, sectoral knowledge gaps and the policies and technologies that could bridge the gap between potential and realization were analysed. Promising examples across the world exist that are pioneering the legal, regulatory, and financial tools that can help unlock the true potential of Wastewater Resource Recovery Facilities (WRRFs) and make the major actors in the bio – circular economy.

By examining the fundamental methodologies and aspects to be considered while carrying out such assessments, an attempt has been made to provide an initial body of reference that can help analysts, decision-makers, plant managers, and consultants to understand the linkages and relationships between the various aspects of sustainability and their consideration while evaluating energy recovery systems. The preliminary assessment indicators can help provide the information for methodological advice that can be useful for any decision maker exploring the possibility of recovering biogas from sewage sludge or wastewater resources.

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Annexure 1 – Calculation Methodologies for Indicators

This annexure discusses the methodologies, equations, and assumptions employed to quantify the indicators employed for assessing the sustainability of biogas recovery systems in wastewater treatment plants.

Technical Indicators (used values are available in Table 22):

Biogas Generation Potential from UASB reactors for wastewater treatment

The biogas generation potential from anaerobic treatment of domestic wastewater can be estimated by the following equation proposed by (Lemos Chernicharo, 2007) and used by (Silva dos Santos et al., 2018):

$$Q_{BGAR} = Q_{SEW} * \frac{[S_0(1-Y)-S]}{f(T) * C_{CH_4}} * (1 - I_L) \qquad \textit{Equation 2}$$

Equation 2 describes the theoretical biogas flow that can be produced in an anaerobic digester (Q_{BGAR} in m^3/year). The description of various factors is given in Table 28 along with assumed values. These values have been proposed by (Lemos Chernicharo, 2007) and used by (Silva dos Santos et al., 2018) for their estimation of biogas potential in Brazil.

Table 28 – Parameters for calculating biogas generation potential from UASB wastewater reactors (Silva dos Santos et al., 2018)

Variable	Unit	Description	Assumption
Q_{SEW}	m^3/year	total sewage flow into the anaerobic reactor	As per actual (Table 22)
S_0	kg/m^3	influent chemical oxygen demand (COD) concentration to the reactor	As per actual (Table 22)
S	kg/m^3	effluent chemical oxygen demand (COD) concentration	As per actual (Table 22)
Y	kg COD_{sludge}/kg COD_{in}	solid production yield	0.17
f(T)		volumetric correction factor due to temperature	
C_{CH4}	%	Concentration of methane in biogas	60%
I_L	%	loss index of gas in the reactor due to leakage or dissolution	40%

The total sewage flow into the WWTP and the anaerobic reactor (Q_{SEW}) is a function of the contributing population and the wastewater generated per capita per day in (m^3/capita.day). A value of 0.15 m^3/capita.day can be assumed if the local wastewater generation data is not available (Lemos Chernicharo, 2007).

The volumetric correction factor f(T) is calculated according to the equation:

$$f(T) = \frac{P \times K}{R \times T} \quad \text{Equation 3}$$

Where P = atmospheric pressure (1 atm); K = COD consumed for production of 1 mol of CH_4 (64 g COD/mol); T = average ambient temperature (298 K); R = universal gas constant (0.08206 atm.L/mol.K)

Biogas generation potential from anaerobic sludge digesters for sludge treatment

For biogas recovery from sewage sludge, the methodology suggested by (Andreoli et al., 2007) is utilized based on the following formula:

$$Q_{BGSS} = \frac{SS \times (VS{:}TS) \times E \times Q_{BGVS} \times P_{con} \times 365}{1000} \quad \text{Equation 4}$$

The equation relates the biogas production in an anaerobic sludge digester with the volatile solids destruction, which is dependent on the volatile-to-total solids ratio (VS:TS) and the volatile solids removal efficiency (E). The variables are defined in the Table 29 below.

Table 29 – Parameters for calculating biogas potential from anaerobic sludge digesters (Andreoli et al., 2007)

Variable	Unit	Description	Assumption
Q_{BGSS}	m^3/year	Potential biogas generation from anaerobic digestion of sludge	
SS	gSS/inh.day	Mass of sludge directed to the sludge treatment stage	70 (UASB*) 15 (after CAS**)
VS:TS		Volatile-to-total solids ratio	0.775 (UASB) 0.575 (after CAS)
E	%	Volatile solids removal efficiency	47.5%
Q_{BGVS}	m3/kg VS destroyed	Biogas production rate per kg of VS destroyed	0.95
P_{con}	inhabitants	Contributing Population	As per actual

**UASB – Upflow anaerobic sludge blanket reactor **CAS – Conventional activated sludge process*

Electricity Generation Potential

The electricity generation potential from biogas recovery can be calculated using the following equations. The electric power (P in KW) can be determined using the available biogas flow. The potential electrical energy (E in GWh/yr) can then be calculated from the electric power available (Silva dos Santos et al., 2018).

$$P = \frac{LHV * \eta * Q_{BG} * C_{CH_4}}{31536} \quad \text{Equation 5}$$

$$E = \frac{P * \Delta t * f_c}{10^6} \quad \text{Equation 6}$$

The various factors in the equation are described in Table 30 below.

Table 30 – Parameters for calculating electrical energy generation potential (Silva dos Santos et al., 2018)

Variable	Unit	Description	Assumption
P	**KW**	**Electric power produced**	
LHV	MJ/m^3	Lower heating value of methane	35.5
η	%	Efficiency of the energy conversion technology	33
Q_{BG}	m^3/year	Biogas flow in Anaerobic Digesters	
C_{CH4}	%	Concentration of methane in biogas	60
		Factor for unit adjustment	31536
E	**GWh/yr**	**Annual Potential Electrical Energy**	
Δt	hours/yr	Annual hours of operation	8760
f_c		Annual capacity factor of the plant	0.8

Heat Generation Potential

The heat generation potential is the amount of heat energy that can be generated from using the biogas as a fuel in a combined heat and power engine. Using the method applied by (Akbulut, 2012) in their analysis of biogas potential in a farm-scale biogas plant in Turkey, we can estimate the heat energy generation potential from the biogas recovered in WWTPs. It is to be noted that this is a preliminary estimation of heat energy generation potential, and will vary according to the process conditions, losses, and recovery efficiencies of different technologies.

The heat generation (GWh/yr) from biogas produced in WWTP is given by the following equation:

$$E_{th} = \frac{Q_{BG} * LHV_{BG} * \eta_{th} * f_c}{10^6} \qquad \textit{Equation 7}$$

The various factors in the equation are described below

Table 31 - Parameters for calculating thermal energy generation potential (Akbulut, 2012)

Variable	Unit	Description	Assumption
E_{th}	**GWh/yr**	**amount of thermal energy from biogas**	
Q_{BG}	m^3/year	Biogas flow in Anaerobic Digesters	As per actual
LHV_{BG}	kWh/m^3	Lower calorific value of biogas	5.5
η_{th}	%	Thermal efficiency of energy conversion technology	45
f_c		Annual capacity factor of the plant	0.8

Economic Indicators:

Economic Value of electricity generated:

The economic value of electricity generated from biogas is dependent on the local price of grid electricity in the vicinity of the wastewater treatment plant. We can use the following equation to calculate the economic value of electricity:

$$EV_{el} = P_{el} * E \qquad \textit{Equation 8}$$

Where EV_{el} is the economic value of the generated electricity (€/year), P_{el} is the local tariff of grid electricity in the WWTP region (€/kWh); E is the amount of annual generated electricity (kWh/year).

Economic Value of heat generated:

If fossil fuels are used to generate heat within the WWTP, it is assumed that the cost of fossil fuels needed to generate an equivalent amount of heat energy will be the economic value of heat generated. As the heat generated in CHP from biogas recovered in WWTPs will replace the use of fossil fuels, it can be assumed that the heat energy holds an equivalent economic value to the cost of fossil fuels. The economic value is thus calculated by the following equation:

$$EV_{th} = \frac{P_{ff} * E_{th}}{LCV_{ff}} \qquad \textit{Equation 9}$$

Where EV_{th} is the annual economic value of heat energy generation from biogas recovery (€/year); P_{ff} is the local cost of the specific fossil fuel (€/m^3 or €/litre) used for heat generation in the WWTP (e.g. natural gas, diesel, coal, etc.); E_{th} is the annual thermal energy generated as calculated in previous indicators (kWh/year); LCV_{ff} is the energy content of the specific fossil fuel used (kWh/m^3 or kWh/litre)

It should be noted that these are strictly indicative values of the economic benefits that can be accrued from biogas recovery in WWTPs. These costs exclude the energy and materials needed to operate the digester and CHP, the infrastructure costs, operation and maintenance costs, and other running costs that must be incurred to implement and operate a biogas recovery system. A thorough financial analysis using methodologies such as Net Present Value (NPV) and Internal Rate of Return (IRR) must be conducted using site-specific cost data to get a more holistic understanding of the costs and benefits of such biogas recovery systems. However, these preliminary economic values can provide useful information to indicate the potential savings that can be achieved in terms of electricity and fossil fuel consumption for the WWTP.

Levelized cost of biogas production

The levelized cost of biogas indicates the cost of producing a unit of biogas over the project lifetime. The discounting rate is used to annualize the costs and biogas production from each year of the project lifetime. The annualized costs and production values are summed for the project lifetime, giving the overall levelized cost of biogas production. It is expressed in the unit of (EUR/m^3 of biogas produced). The following formula has been used in this research based on widely used levelized cost of electricity (LCOE) calculation methodologies (U.S. Department of Energy, 2015).

$$LCOB = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{Bio_t}{(1+r)^t}}$$ *Equation 10*

Where,

n = Project lifetime (years)

I_t = Investment cost in year t (including financing) (in EUR)

M_t = Operations and maintenance costs in year t (in EUR)

F_t = Fuel costs in year t – including electricity and fossil fuels (in EUR)

Bio_t = Discounted annual biogas production in year t (in m^3/year)

r = Discount rate (assumed to be 10%)

Formula based on levelized cost of electricity formula used by (U.S. Department of Energy, 2015)

The costs taken for this project are based on the actual costs for the Gardabani and assumed to be using a upflow anaerobic sludge blanket reactor (UASB) for wastewater treatment and an anaerobic sludge digester for biogas recovery from sludge. For actual cost derivations and formula sources, please refer to Table 25.

Environmental Indicators

Fossil fuel use avoided:

It can be beneficial for decision makers to understand the amount of fossil fuel use that can be avoided by recovering biogas and utilizing it for heat and electricity generation. For the quantification of this indicator, it is assumed that the use of fossil fuel is avoided only from the direct consumption of fossil fuels inside the WWTP for heat generation. Grid electricity generation from fossil fuels cannot be sufficiently quantified for this indicator. The quantity of avoided fossil fuel can be calculated as follows:

$$Q_{ff} = \frac{E_{th}}{LCV_{ff}}$$ *Equation 11*

Where, Q_{ff} is the quantity of fossil fuel use avoided in m^3/year or litres/year; E_{th} is the heat energy recovered from biogas annually (kWh/year); LCV_{ff} is the energy content of the specific fossil fuel used (kWh/m^3 or kWh/litre). If more than one fossil fuels are utilized for heat generation, the same methodology can be used for calculating the avoided quantities of each type of fuel.

Avoided emissions from electricity usage:

Emissions avoided from electricity generation can be calculated by using the emission factor for grid electricity in the country (Silva dos Santos et al., 2018). The country level grid electricity emission factors are available from various databases. The IGES database (Institute for Global Environmental Strategies, 2019) has been used for the purposes of this study. Since biogas is a non-fossil fuel gas, it is considered biogenic and the emission factor for biogas plants is assumed to be zero (dos Santos et al., 2016b). Using the methodology used by Silva dos Santos, the avoided emissions can be calculated as follows:

$$E_{av,el} = E * E_f$$ *Equation 12*

Where, $E_{av,el}$ is the emissions avoided by utilizing biogas for electricity generation per year (tCO_2eq/yr); E is the annual electricity generation from biogas in WWTPs as calculated above (GWh/yr); E_f is the CO_2 emission factor of the grid electricity matrix in the site country (tCO_2/GWh).

For a more comprehensive assessment of potential for emissions reduction from wastewater treatment plants, the Clean Development Mechanism ACM0014 Methodology – Treatment of Wastewater can be employed (Clean Development Mechanism - UNFCCC, 2019)

Avoided emissions from heat energy usage:

Emissions avoided from replacing fossil fuels with biogas for heat generation can be calculated using the stationary combustion emission factors for various fossil fuels. These are available in public databases used for GHG accounting. The GHG Protocol Cross Sector Tool for emission factors (GHG Protocol, 2019) has been used for this study. The avoided emissions can be calculated as follows:

$$E_{av,th} = E_{th} * EF_{ff}$$ *Equation 13*

Where, $E_{av,th}$ are the emissions avoided from use of biogas for thermal energy (tCO_2/yr); E_{th} is the annual thermal energy generation potential as calculated earlier (GWh/yr); Ef_{ff} is the emission factor of the specific fossil fuel per unit of energy (tCO_2/GWh).

Annexure 2 - Gardabani Wastewater Treatment Process

Gardabani WWTP has been recently rehabilitated by STRABAG SE as a contractor to GWP. The company had a technical obligation for reconstruction of the plant by May 2018 and signed the contract with STRABAG SE in August 2017. The reconstruction project included the design, construction, and authorization of the below mentioned WWTP process units:

- Coarse and fine Screen Stages
- Grit and Grease Removal Chambers
- Primary Sedimentation Tanks
- Primary Sludge Pumping Stations
- Sludge Stabilization Tank
- Chemical Dosing Station
- All other required civil, mechanical, electrical works, which also includes a SCADA system for efficient monitoring and control of the plant operation and processes (STRABAG, 2017)

As of September 2018, the plant had been reconstructed, with the treatment process being tested and monitored for final handover. An official confirmation of completion of the reconstruction project has not yet been published.

Currently, the wastewater treatment operation at Gardabani utilizes a return activated sludge system. The activated sludge process is a well-developed and globally utilized wastewater treatment process that employs a multi-chamber layout, using highly concentrated microorganism colonies to degrade the organic matter in wastewater, and remove nutrients to achieve the quality standards set for the effluent water from the WWTP. While there is a variety of process layouts, there are three principle components that are essential for an activated sludge process: i) An aeration chamber, which also acts as a bio rector for aerobic digestion; ii) a settling chamber (or clarifier) where the sludge solids are separated from the treated waste water; iii) A return activated sludge (RAS) system to transport the settled activated sludge (AS) from the clarifier to the aeration chamber (Tilley et al., 2014).

The process begins at the aeration chamber, where a mixture of raw sewage or wastewater is mixed with organisms in the presence of atmospheric air or pure oxygen to produce the biological floc (or AS). The oxygen or air is added to maintain suitable aerobic conditions in the aerobic chamber to sustain the organism colonies. The organisms in the biological floc oxidize the organic carbon matter in the sewage and produce new cells, water, and carbon dioxide. These biological (and sometimes chemical) processes in the aerobic condition are effective at reducing the levels of biodegradable, soluble, and particulate matter in the influent. The removal efficiency is affected by different process conditions, including the hydraulic retention time (HRT), the influent nutrient loads (BOD, COD, N, P, etc.), food to microorganism ratio (F:M ratio), available oxygen, temperature, and more. The mixture of sewage and biological floc is usually referred to as the mixed liquor, and a dry solids concentration (MLSS) of 3 to 6 g/L is common for the process. At the outlet of the aeration chamber, the mixed liquor is transported to sedimentation tanks or clarifiers where the activated sludge settles to the bottom of the tanks. The supernatant (treated WW) is then transported for further treatment or is discharged to a natural water source. The settled sludge (RAS) is collected and pumped back to the inlet of the aeration chamber, where it is used to re-seed the new batch of influent wastewater. As the biological mass is continuously growing in the aeration chamber, the RAS eventually exceeds the designed MLSS concentrations. It is a common practice to divert a portion of the RAS from the loop to maintain the desired MLSS levels and F:M ratio in the aerobic tank. This is usually referred to as the waste activated sludge (WAS) and requires further treatment or stabilization prior to proper disposal (Rieger, L., Guillot, S., Langergraber, G., Ohtsuki, T., Shaw, A., Takacs, I., Winkler, 2012).

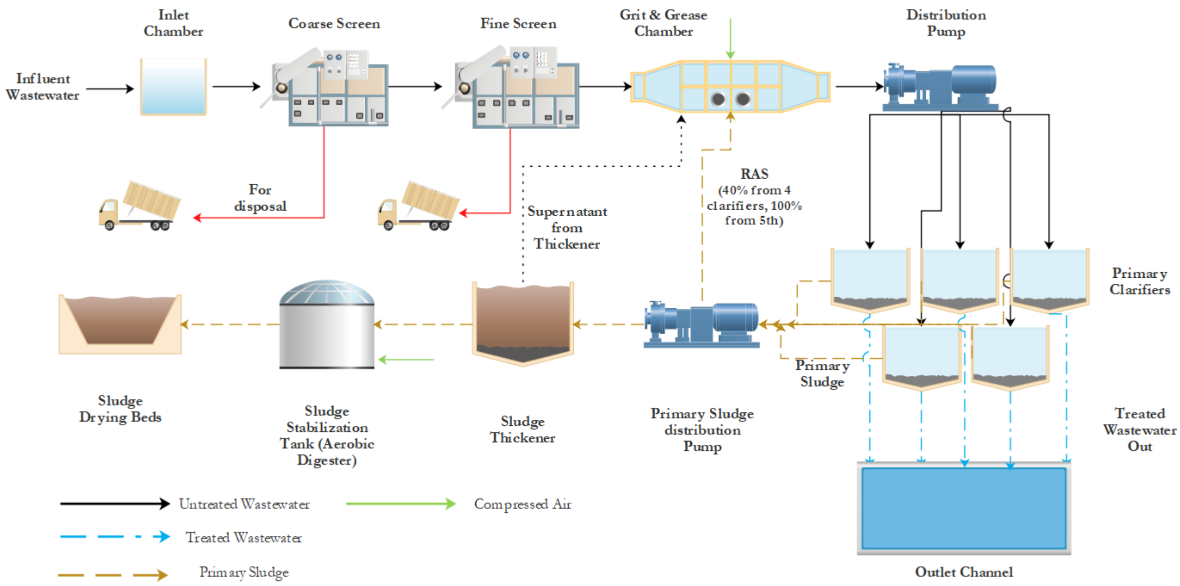

Figure 25 - Schematic Process Diagram of Gardabani WWTP. (Layout by author)

Some of the major advantages and disadvantages of an activated sludge system are:

+ Resistance to sudden variations in hydraulic or organic loads
+ Wide operating range of loading rates
+ High reduction of BOD and pathogens possible
+ Easily modifiable to achieve specific discharge quality standards
– High energy consumption as a constant process
– Capital costs and operating costs are high
– Skilled personnel required for operation and maintenance
– Can be prone to complex microbiological or chemical issues
– Sludge and water effluents need further treatment before discharge

In the case of Gardabani WWTP, the rehabilitated process closely follows the above-mentioned process flow, along with an additional sludge treatment stage. A detailed explanation along with site pictures is given below. All pictures shown below have been taken by the author during his field visit to the plant:

Wastewater Treatment Line

Inlet Chamber:

The influent wastewater from Tbilisi, Rustavi, and the Azoti Chemical Plant is transported to the WWTP by the main trunk sewer, which empties into the inlet chamber at the head of the treatment process. While there was an existing inlet chamber, a new one has been constructed to allow for greater loads. The inlet chamber has large traps to capture large objects such as bottles, trees, dead animals, etc., that can be transported along with the wastewater. There is an automatic water sampling machine at the inlet which takes multiple samples for water quality monitoring throughout the day and relays the results to the process management personnel via a SCADA system. The samples taken are examined for water temperature, dissolved oxygen, and pH levels by the machine.

Figure 26 - Inlet chamber with large traps (Image taken by author)

Coarse and Fine Screening:

The influent wastewater then flows from the inlet chamber to the first stage of mechanical treatment: the coarse screen stage. This stage removes large objects that may have passed through the inlet chamber and could create problems in further processes. The coarse screening consists of a series of rake screens attached to a vertical conveyor belt, where the gap in the rake teeth is 8 mm. The influent wastewater flows through the screens, where the screens pick up on large objects and carry them upwards and out of the water. The screens then dump the picked objects onto another horizontal conveyor belt, which transports the removed objects to a dumping bin. The bin is periodically emptied into a truck and the removed objects are taken to a nearby landfill for disposal. The wastewater then moves to the Fine Screen Building where the same process is repeated in the fine screening stage, with the difference being that the rake teeth gap is 4-6 mm. This facilitates the further removal of smaller objects that may have passed through the coarse screens. This double screening provides an effective filtration of the influent wastewater before further biological and mechanical treatment.

Figure 27 - a) Vertical conveyor with coarse screen b) Rake arrangement in screen. (Images taken by author)

Grit and Grease Removal Chamber (Aerobic chamber)

The grit and grease removal is an important stage in the return activated sludge process. It serves to remove the grit and fats from the wastewater, as well as acting as an aerated chamber for the breakdown of biodegradable components by aerobic digestion. This stage consists of 4 rectangular chambers, with automatic scrapers running above the water surface. Pure oxygen is added at this stage to improve the environment for microbial activity in the wastewater. Two of the chambers are used for grit removal, while the other 2 are used for grease removal. Wastewater is fed to the chambers from the fine screen building via 4 channels, while the RAS is fed through a single channel combining the flow from 5 clarifiers. 40% of the settled activated sludge from 4 clarifiers, and 100% of the AS from the 5th clarifier is fed to the grit and grease chamber. The HRT in the grit and grease chamber ranges from 1-3 days depending on the water load. The grit and grease is periodically removed by the scrapers and deposited in a separate chamber, where it is extracted and disposed in the landfill.

Figure 28 - Grit and Grease Chambers. Compressed air pipes are visible on the side of the chambers (Image taken by author)

Primary Clarifiers

The wastewater is then transported to 5 identical primary clarifiers or sedimentation tanks. The clarifiers existed in the original plant process but had fallen into disrepair (figure) The rehabilitated clarifiers are based on the same infrastructure, though one of the clarifiers has been repurposed as a sludge stabilization tank. There are 4 old clarifiers that have not been rehabilitated and are currently unused. The clarifiers have a circular shape and are large enough to allow the settling of the sludge content in the influent wastewater. Floating materials such as grease and other particles rise to the surface and are continually removed by automatic surface skimmers that keep rotating. The clarifiers are also equipped with scrapers at the bottom that are continuously driven to remove the settled sludge from the clarifier bed and direct it towards a hopper situated in the base of the clarifier, from where it goes to the sludge pumping station. A fraction of the collected sludge is then pumped back to the grit and grease chambers as RAS and the rest is sent to the thickener for further sludge treatment. The supernatant (treated water) from the clarifiers is then discharged into the outlet channel, where a final measurement for pH, temperature, and dissolved oxygen is taken before being discharged to the Mtkvari River. This marks the end of the wastewater treatment line.

Figure 29 - Primary clarifiers after rehabilitation (Image taken by author)

Figure 30 - Primary clarifier before rehabilitation. Source - (Shubitidze, 2006)

Sludge Treatment Line

Sludge Thickener

Sludge thickening is the first process of the sewage treatment line, aided by a newly built gravity thickener. The gravity thickener is similar in structure to sedimentation tanks, and consists of a circular, centre-fed tank, with sludge removal from the bottom, and supernatant extraction from the perimeter. 60% of the generated primary sludge from four of the clarifiers is routed to the thickener, where it stays for 10-12

Figure 31 - Sludge thickener (under construction) (Image taken by author)

days to enable the separation of the primary sludge from the supernatant. The thickened sludge settles to the bottom and the supernatant starts floating at the top. The supernatant from the thickener (untreated wastewater) is taken to the grit and grease chamber where it joins the wastewater treatment line for further treatment.

The settled sludge is pumped through the thickened primary sludge pumping station to the aerobic digester used for sludge stabilization. (Shubitidze, 2006)

Sludge Stabilization Tank (Aerobic Reactor)

The sludge stabilization tank is an aerobic digestion reactor which is used for further treatment of the sludge from the thickener. One of the old clarifiers was rehabilitated and repurposed as an aerobic digestion reactor for sludge stabilization. The HRT for this stage is 15-20 days depending on the characteristics of the incoming sludge. The thickened sludge is pumped to the stabilization tank and subjected to a constant aeration with compressed air. The micro-organisms start aerobically oxidising the biodegradable organic matter in the sludge and release carbon dioxide, ammonia, and water in the process. The digested sludge is then taken to the digested sludge pumping station which further pumps it to the sludge drying beds.

Figure 32 - Sludge Stabilization Tank (Image taken by author)

Drying Beds

The sludge drying beds are the last treatment stage in the sewage treatment line. The WWTP has 10 sludge drying beds that have a total surface area of about 20 hectares, with each bed measuring 200 x 100 m in dimensions and having a gradient from 0.4 m to 1.6 m in the deep end to aid the dewatering of the sludge. At the time of the visit, the sludge treatment process had not been completely commissioned and only two of the beds were being employed. The drying beds have enough capacity to store the sludge for at least a year of full-scale operations. However, the dried sludge in the beds can be utilized as an effective organic fertilizer and presents an opportunity for further resource reuse of the sludge. The sanitary inspectorate has tested the sludge on the site and confirmed that heavy metals are not present in the sludge and thus can be safely used as a fertilizer for agricultural purposes. The drying beds mark the end of the sewage treatment line.