COMPARISON OF ENERGY CONSUMPTION AND CARBON FOOTPRINT OF WASTEWATER TREATMENT SYSTEMS THROUGH MODELING

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COMPARISON OF ENERGY CONSUMPTION AND CARBON FOOTPRINT OF WASTEWATER TREATMENT SYSTEMS THROUGH MODELING

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ABSTRACT

COMPARISON OF ENERGY CONSUMPTION AND CARBON FOOTPRINT OF WASTEWATER TREATMENT SYSTEMS THROUGH MODELING

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With increasing population and developing regulations, wastewater treatment plants (WWTP) have started to become a higher energy consuming sector in order to serve higher capacities. In the design and management phases of a treatment plant, energy consumption and carbon footprint of the plant should be considered. In this regard, hypothetical and real case models are created to simulate and compare WWTP systems. In this thesis study, first, municipal WWTPs of Turkey were analyzed to determine the traditional technologies concerning biological treatment and sludge stabilization of municipal wastewaters. Combinations of different units and processes were used to build 105 hypothetical WWTP models. These models were then used to determine sludge production amount, energy consumption, and carbon footprint. It was observed that specific energy consumption ranged between 0.002 kWh/m^3 and 0.89 kWh/m^3, while, carbon footprints varied between 588 kgCO_2eq/h and 5,697 kgCO_2eq/h. In addition, Bursa East Domestic WWTP was considered for the simulation-based optimization of a real WWTP. It was shown that both energy consumption and carbon footprint of this treatment plant can be reduced by 10%.

Keywords: Municipal Wastewater Treatment Plant, Energy Consumption, Carbon Footprint, Modeling, BioWin

ÖZ

MODELLEME İLE ATIKSU ARITMA SİSTEMLERİNİN ENERJİ TÜKETİMİ VE KARBON AYAK İZİ KARŞILAŞTIRMASI

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Artan nüfus ve değişen yönetmelikler ile birlikte, atıksu arıtma tesisleri (AAT) yüksek kapasitelere hizmet edebilmek için daha fazla enerji tüketen bir sektör haline gelmeye başlamıştır. Arıtma tesislerinin tasarım ve işletme safhalarında enerji tüketimi ve karbon ayakizinin göz önünde bulundurulması gerekmektedir. Bu bağlamda, AAT sistemlerinin simulasyonu ve karşılaştırılması için hipotetik ve gerçek durum modelleri yaratılmıştır. Bu tez çalışmasında, ilk olarak, belediye atık sularında kullanılan biyolojik arıtım ve çamur stabilizasyon teknolojilerini belirlemek amacıyla, Türkiye'nin belediye atıksu arıtma tesisleri analiz edilmiştir. Farklı birimlerin ve teknolojilerin kombinasyonları kullanılarak 105 varsayımsal AAT modeli oluşturulmuştur. Bu modeller daha sonra çamur üretimi, enerji tüketimini ve karbon ayak izini belirlemek için kullanılmıştır. Spesifik enerji tüketiminin 0,002 kWh/m^3 ile 0,89 kWh/m^3 arasında değiştiği, karbon ayakizinin ise 588 kgCO_2ed/saat ile 5.697 kgCO_2ed/saat arasında değiştiği gözlenmiştir. Öte yandan, gerçek bir AAT'nin simülasyon temelli optimizasyon çalışması için Bursa Doğu Evsel Atıksu Arıtma Tesisi kullanılmıştır. Bu gerçek tesisin hem enerji tüketimini hem de karbon ayakizini %10 oranında azaltılabildiği gösterilmiştir.

Anahtar Kelimeler: Evsel Atıksu Arıtma Tesisi, Enerji tüketimi, Karbon Ayakizi, Modelleme, BioWin

To my parents who always supported me…

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ABBREVIATIONS	
AAO	Anaerobic Ammonia Oxidizers
ADM	Anaerobic Digestion Model
AOB	Ammonium Oxidizing Bacteria
AS	Activated Sludge
ASM	Activated Sludge Model
BNR	Biological Nutrient Removal
BOD	Biological Oxygen Demand
CHP	Combined Heat and Power
CMAS	Completely Mixed Activated Sludge
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
GHG	Greenhouse Gas
GWP	Global Warming Potential
HRT	Hydraulic Retention Time
HS	High Strenght
IR	Internal Recycle
LCA	Life Cycle Assessment
LS	Low Strenght
MGD	Million Gallons per Day
MLSS	Mixed Liquor Suspended Solids

MS	Medium Strenght
MTL	Million Turkish Liras
NOB	Nitrite Oxidizing Bacteria
NPV	Net Present Value
OD	Oxidation Ditch
OHO	Ordinary Heterotrophic Organisms
PAO	Phosphorus Accumulating Organisms
PE	Population Equivalence
PS	Primary Sludge
RAS	Return Activated Sludge
SEC	Specific Energy Consumption
SRT	Sludge Retention Time
TN	Total Nitrogen
TP	Total Phosphorous
TSS	Total Suspended Solids
WAS	Waste Activated Sludge
WW	Wastewater
WWTP	Wastewater Treatment Plant

CHAPTER 1

INTRODUCTION

Urbanization became inevitable after the industrial revolution as urban environments provide better employment opportunities, better social services, and better merchandising opportunities for people. However, this movement has its downsides. It is well known that generated pollution load and wastewater amount are mostly dependent on population increase and related residential and industrial activities (Qin et al., 2014). Wastewater treatment processes are widely used to remove organics and pollutants from wastewater to prevent waterborne diseases and minimize environmental pollution (Stensel et al., 2014). Therefore, wastewater treatment plants (WWTPs) became one of the primary substructures for human-made habitat. On the other hand, the WWTPs are becoming more massive due to the effective population needed to be served (Chai et al., 2015). In Turkey, the amount of wastewater treated in WWTPs was recorded as 3,257 million m^3 in 2012. In 2016, the number increased to 3,842 million m^3 (TUIK, 2016b). The number and capacity of domestic WWTPs are expected to increase in the following years due to the increase in the population and the effects of urbanization.

Today, 25% of the energy consumption in the water sector is used for wastewater collection and treatment (Li et al., 2019). This energy corresponds to 1 to 4% of total energy consumption worldwide (IEA, 2016). Moreover, by 2040, the energy used for wastewater works will exceed 60% of the total energy used in the water sector if the demands are as projected (IEA, 2016). This problem drew attention to energy efficiency studies on this subject. However, there is no legislation or limitation on energy consumption in WWTPs. So, energy consumption varies significantly among different treatment plants.

Energy consumption is considered as a global problem for humankind, especially considering the related greenhouse gas (GHG) emissions. Many countries are struggling to convert energy resources from fossils to renewables. As long as the renewables could not dominate the energy production market, the carbon footprint of the energy production will remain one of the most carbon releasing industries of our planet (Ashrafi et al., 2014). In addition to the GHGs generated by energy consumption, it can be observed that GHGs are emitted directly from WWTPs. These GHGs are CO_2, CH_4 and N_2O (Delre et al., 2019). These gasses are also the most significant contributors to climate change (IPCC, 2014). When energy consumption and GHG emissions due to treatment processes are considered, the global warming effect of a domestic WWTP needs consideration.

Wastewater treatment facilities contain physical, chemical and biological sub-process and are controlled mostly by experience. Therefore, these facilities are not operated optimally (Wei, 2013). Modeling and optimization studies are being developed for these facilities with the development of tools and simulation software used. (Henze et al., 2017). With simulation software, a treatment process can be modeled to use for decision-making to reach optimal WWTP design or finding optimal operational settings to improve the facility in terms of energy and carbon footprint efficiencies.

This thesis study aims to;

- Compare treatment efficiencies and sludge production amounts in typical municipal WWTP schemes in Turkey via BioWin simulations. This would provide numerical values for the comparison of expected sludge productions for different treatment schemes for given influent and effluent characteristics. Predicted sludge production amounts would also provide inputs for energy and carbon footprint calculations for various treatment schemes.
- Compare common municipal WWTP schemes in Turkey in terms of their carbon footprint and energy consumption to evaluate the potential importance of carbon footprint and energy consumption in treatment scheme selection.

- Optimize the operation of a real WWTP in terms of its energy carbon footprint and energy consumption using a simulation-based approach. Alternative methods are suggested and evaluated to optimize process.

The objectives provided above are covered in individual chapters. First, information on municipal WWTPs of Turkey was analyzed to determine the traditional technologies concerning biological treatment and sludge stabilization of municipal wastewaters. Combinations of different units and processes were used to build a set of WWTP models. These models were then used to determine relevant sludge production amounts, energy consumptions, and carbon footprints. Bursa East Domestic WWTP was employed for the simulation-based optimization of a real WWTP.

CHAPTER 2

LITERATURE REVIEW

2.1. Wastewater Treatment

It was observed that there is a relationship between wastewater disposal and public health (Naik et al., 2012). However, on this issue, solutions had been developed long before this knowledge. In the 19th century, the initial attempts to treat wastewater started in Manchester UK (Salgot et al., 2018). Since then, several treatment approaches and schemes have been developed to meet effluent discharge criteria for different types of wastewaters.

2.1.1. Biological Treatment Configurations for BOD/COD removal

In 1913, Arden and Lockett developed a full scale activated sludge (AS) process (Ardern et al., 2007). This method became the most common biological treatment process in the world (Scholz, 2015). AS process consists of two separate phases. In the first phase, the principle is to breed mixed microbial population with constant aeration and mixing (in aeration tank). The main purpose of this phase is to degrade organic pollutants with microbial activity. In order to maintain that treatment, oxygen supply and mixing are essential. Oxygen supply is used for respiration, while mixing is used for assuring the maximum contact between wastewater and microbial flocs. In the second phase, the principle is to separate biosolids from aerated wastewater. There are two objectives in this phase. The first one is clarification of effluent. The second one is to return flocculated biomass to the aeration tank in order to maintain biomass suspension in the system (Scholz, 2015; Stensel et al., 2014). The schematic representation of AS process is provided in Figure 2-1 (Rieger et al., 2012).

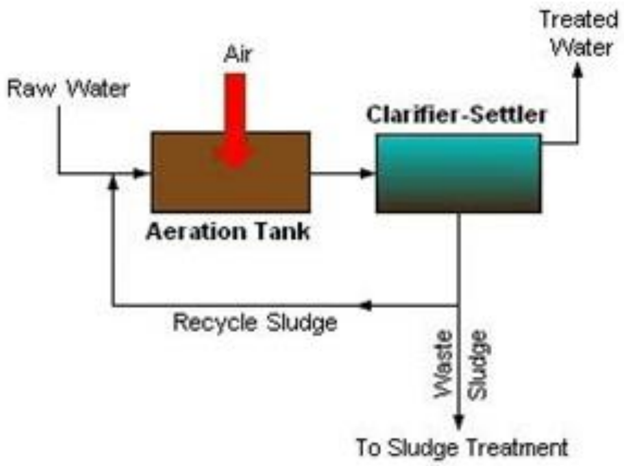

Figure 2-1. The Diagram of AS Process (Rieger et al., 2012)

AS is well suited for treating organic carbon-containing wastewaters. This attribute made the process widely used by municipalities and industries, where wastewater may constitute municipal sewage, textile wastewaters, petroleum wastewaters or any organic chemicals (Cheremisinoff, 2001). AS process is considered as a secondary treatment since the procedure removes dissolved organic matter escaping the primary sedimentation tank (primary treatment), usually located before AS process to remove settleable solids. Physical treatment such as screens and grit chambers, which are the first two units of WWTPs, are called as preliminary treatment (Cheremisinoff, 2001; Stensel et al., 2014). On the other hand, modified AS processes can also treat N and P in the wastewater. These configurations are grouped under biological nutrient removal (BNR) methods (Cheremisinoff, 2001; Stensel et al., 2014).

2.1.2. AS Process Configurations

There are numerous AS process configurations used today. The most common types can be described as follows:

Completely mixed AS (CMAS) process can be considered as one of the conventional kinds among other biological treatment options. A schematic representation of the contact-stabilization process is provided in (Figure 2-2). Mixing in the aeration tank leads to a uniform distribution of mixed liquor suspended solids (MLSS) concentration, organic load and oxygen demand. The most crucial advantage of CMAS is its resistance to shock loads due to the dilution of organic substrate. Therefore, it is suitable for fluctuating load intakes (Stensel et al., 2014).

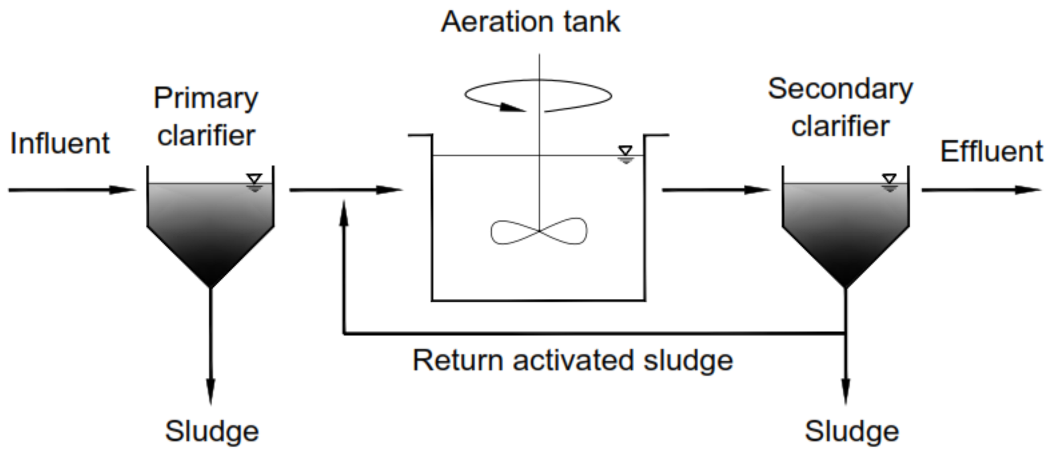

Figure 2-2 The Diagram of CMAS Adapted from Figure 8-1(a) (Stensel et al., 2014)

In plug-flow AS process (Figure 2-3), wastewater and return AS (RAS) enter the system in one point and flow together to the endpoint. Typically, two or four baffles are used to create plug flow channels. In the laminar flow of the system, oxygen demand decreases along with the tank. Aeration rate can be modified from beginning to end of the tank, to match the oxygen demand in the bioreactor (Stensel et al., 2014; Water Environment Federation, 1998). Moreover, there is a modification of this process. If the wastewater is introduced to the system from more than one point, it is called step-feed configuration. This process is used to control/balance oxygen demand and volumetric BOD load (Stensel et al., 2014; Water Environment Federation, 1998).

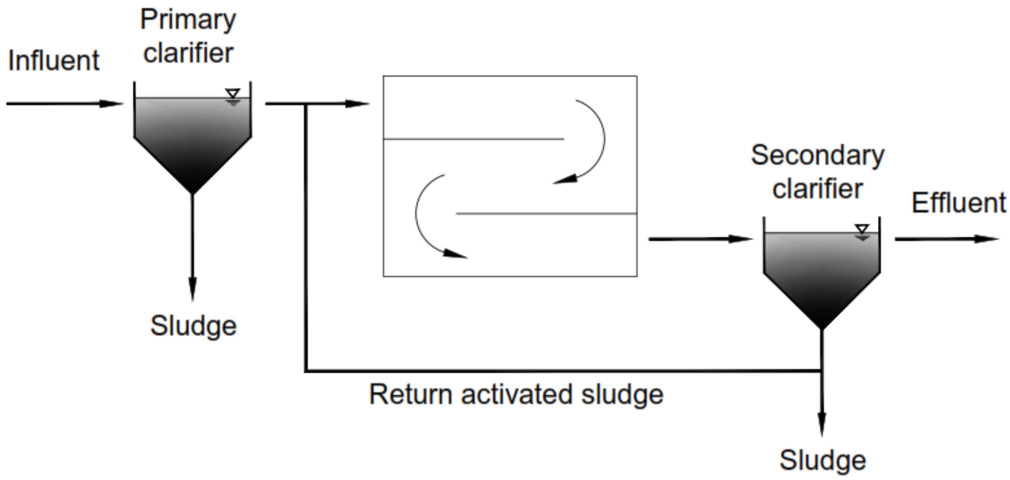

Figure 2-3 The Diagram of Plug-flow Adapted from Figure 8-15 (b) (Stensel et al., 2014)

High rate aeration is used to treat high volumetric BOD loadings. This configuration is similar to CMAS process, yet the difference arises from high wastewater loading rate, high sludge recycle rate and short hydraulic retention time (HRT). However, the removal efficiency of this process is not as high as in CMAS or plug flow systems. In order the keep the system stable, provision of sufficient aeration and mixing is essential in this configuration (Stensel et al., 2014; Water Environment Federation, 1998).

Contact-stabilization is a configuration that uses two separate tanks for contact and stabilization (Figure 2-4). The objective of using a stabilization tank is to stabilize the RAS with aeration. On the other hand, the contact tank aims to introduce stabilized RAS with incoming wastewater for the removal of the soluble BOD. The significant aeration occurs in this section. The contact-stabilization process requires less aeration volume than conventional processes like CMAS or plug-flow processes (Stensel et al., 2014; Water Environment Federation, 1998).

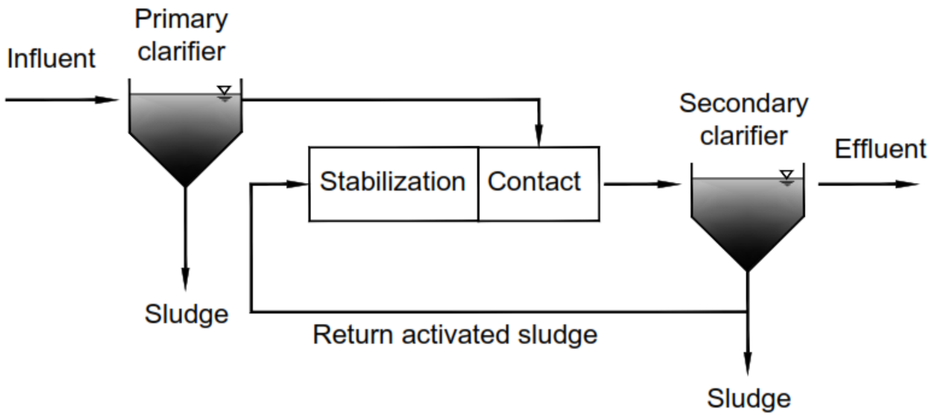

Figure 2-4 The Diagram of Contact-stabilization Adapted from Figure 8-15 (e) (Stensel et al., 2014)

Extended aeration is similar to plug-flow process. The main difference is the higher aeration time needed in order to operate in the endogenous respiration phase of microbial activity. Sludge retention time (SRT) of the system can be up to 30 days. Moreover, HRT of the tank is usually around 24 hours because of the high sludge age. This process is generally used for small communities due to the large tank volume required for aeration and mixing. Besides, extended aeration processes generally do not require primary sedimentation (Cheremisinoff, 2001; Moran, 2018; Stensel et al., 2014).

The oxidation ditch process (Figure 2-5) is an extended aeration process. The reactor shape is oval with centered baffles dividing the reactor into channels. In these channels, desired aeration and mixing occurs. Mixing is achieved by horizontal mixers similar to the ones in the plug-flow process. The mixture provides a velocity of 0.3 m/s to keep the sludge in suspension. Moreover, in this method, partial aeration can be used to achieve nutrient removal in the system (Stensel et al., 2014; Water Environment Federation, 1998).

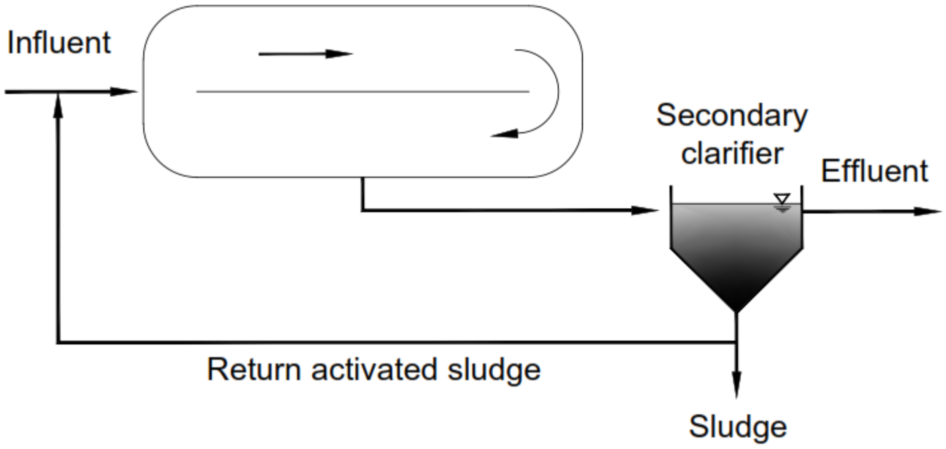

Figure 2-5 The Schematic Diagram of Oxidation Ditch Process Adapted from Figure 8-15 (j) (Stensel et al., 2014)

There are also other systems, such as two-stage CMAS process coupling in series in order to achieve different SRTs. The primary purpose of this process is to treat toxic substances in the first stage. The frequent use can be observed for industrial wastewaters where toxicity is possibly high. On the other hand, for different needs, there are different processes as well. To illustrate, a high-purity oxygen process is used to eliminate the odor and control the volatile organic substance. Moreover, Krous process is used for nitrogen deficit wastewaters. Many more could be found in the literature (Stensel et al., 2014; Water Environment Federation, 1998).

In the following Table 2-1, typical design parameters for commonly used biological treatment processes are given.

Table 2-1 Typical Design Parameters for Commonly Used Biological Treatment Processes Adapted from Table 8-16 (Stensel et al., 2014)

Reactor Type	MLSS (mg/L)	SRT (days)	Total HRT (hours)	RAS (% of influent)
Completely Mix	1,500-4,000	3-15	3-5	25-100
Plug Flow	1,000-3,000	3-15	4-8	25-75
High rate	200-1,000	0.5-2	1.5-3	100-150
Extended aeration	2,000-5,000	20-40	20-30	50-150
Oxidation ditch	3,000-5,000	15-30	15-30	75-150
Contact stabilization	1,000-3,000 6,000-10,000	5-10	0.5-1 2-4	50-150

2.1.3. Biological Processes for Nitrogen Removal

For conventional biological nitrogen removal, two tanks or zones are required which are called aerobic and anoxic. In aerobic zone nitrification occurs, while in anoxic zone denitrification occurs. In aerobic zone, NH_4-N is oxidized to NO_2-N and then to NO_3-N. After the oxidation, reduction to N_2 takes place in the anoxic zone. Nitrification and denitrification equations are given in Equation 1 and Equation 2, respectively (Stensel et al., 2014).

$$NH_4^+ + 2O_2 \rightarrow NO_3^- + H_2O + 2H^+ \qquad (1)$$

$$4NO_3^- + 5CH_2O + 4H^+ \rightarrow 2N_2 + 5CO_2 + 7H_2O \qquad (2)$$

The nitrogen removal processes can be held in single-sludge or two-sludge biological nitrogen removal systems. In a single-sludge process, there is only one sedimentation tank following nitrification and denitrification processes. Single-sludge processes are grouped concerning the location of the anoxic zone, as pre-anoxic, post-anoxic or simultaneous nitrification-denitrification. Internal recycle (IR) might be used to pump mixed liquor from one zone to another in these systems. Two-sludge systems, on the other hand, have separate sedimentation tanks for both aerobic (nitrification) and anoxic (denitrification) tanks. The configurations of these processes are illustrated from Figure 2-6 to Figure 2-8 (Cheremisinoff, 2001; Stensel et al., 2014).

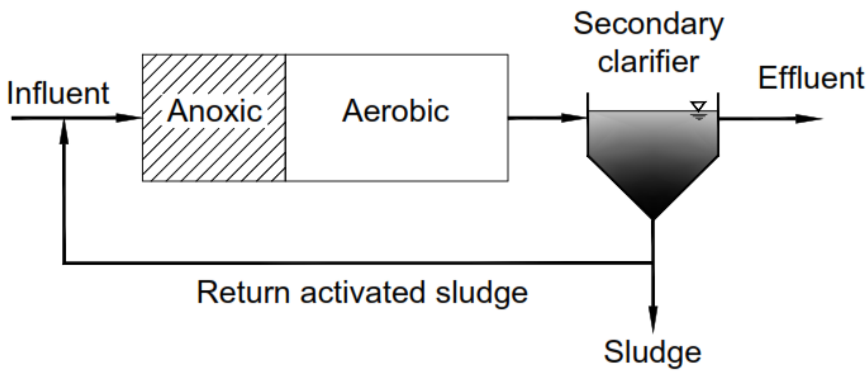

Figure 2-6 The Diagram of Pre-Anoxic Biological Nitrogen Removal Process Adapted from Figure 8-21 (a) (Stensel et al., 2014)

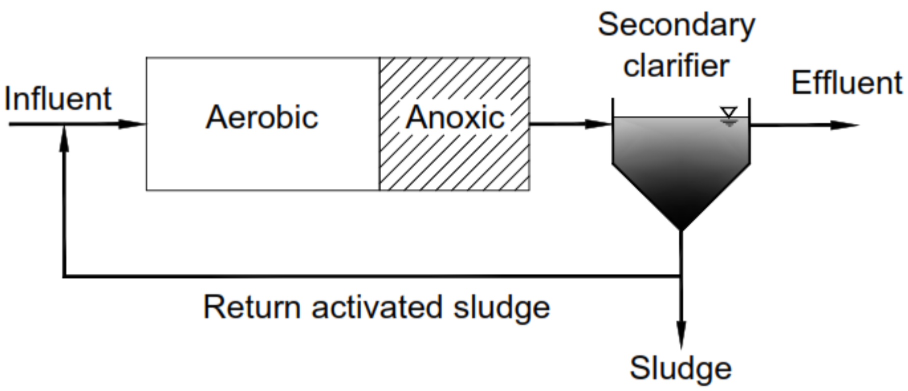

Figure 2-7 The Diagram of Post-Anoxic Biological Nitrogen Removal Process Adapted from Figure 8-21 (c) (Stensel et al., 2014)

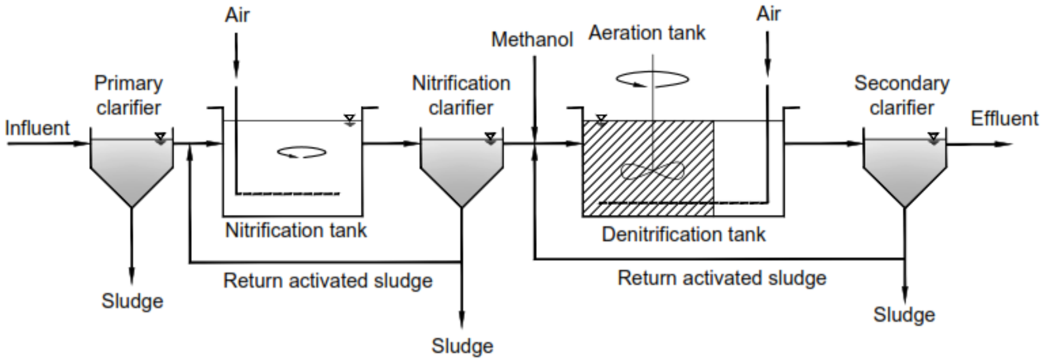

Figure 2-8 The Diagram of Two-Sludge Biological Nitrogen Removal Process Adapted from Figure 8-21 (e) (Stensel et al., 2014)

2.1.4. Biological Processes for Phosphorous Removal

In 1974, it was clarified that volatile fatty acids affect phosphorus removal in aerobic degradation (Rybicki et al., 1997). In the literature, It was stated that anaerobic contact between activated sludge and influent wastewater is needed to accomplish biological phosphorus removal in wastewater. (Rudolfs et al., 1947; Rybicki et al., 1997; Stensel et al., 2014). The most common biological phosphorus removal configuration is called Phoredox (A/O, i.e. anaerobic/oxic) configuration (Barnard, 1975). The setup consists of anaerobic and aerobic sequence with low SRT to target biological phosphorus removal. The schematic representation of A/O process is provided in Figure 2-9.

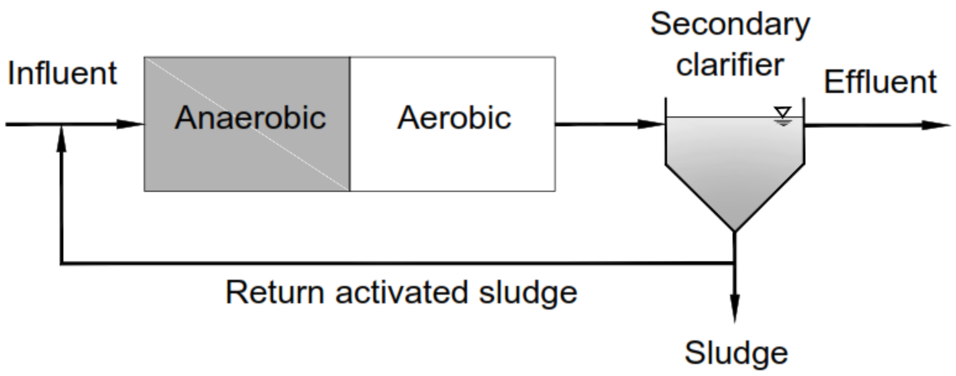

Figure 2-9 The Diagram of A/O Biological Phosphorous Removal Process Adapted from Figure 8-29 (a) (Stensel et al., 2014)

In municipal WWTPs, chemical phosphorous removal is also used besides biological phosphorus removal. In this method, metal salts are added to the secondary sedimentation tank (or before and after sedimentation tank) in order to enhance precipitation of phosphorous (Rybicki et al., 1997).

2.1.5. Biological Processes for Nitrogen and Phosphorus Removal

Biological nutrient removal (BNR) aims for nitrogen, phosphorus or both nitrogen and phosphorus removal in a system. The most basic configuration of BNR systems is A2O (anaerobic/anoxic/aerobic) processes. This process is a modified version of A/O process. The modification is achieved through the addition of an anoxic zone with internal recycle between anaerobic and aerobic regions. Moreover, SRT of the system runs at a range of 5-25 days, which provides nitrification and denitrification besides phosphate removal (Moran, 2018; Stensel et al., 2014). The schematic representation of A2O process is provided in Figure 2-10.

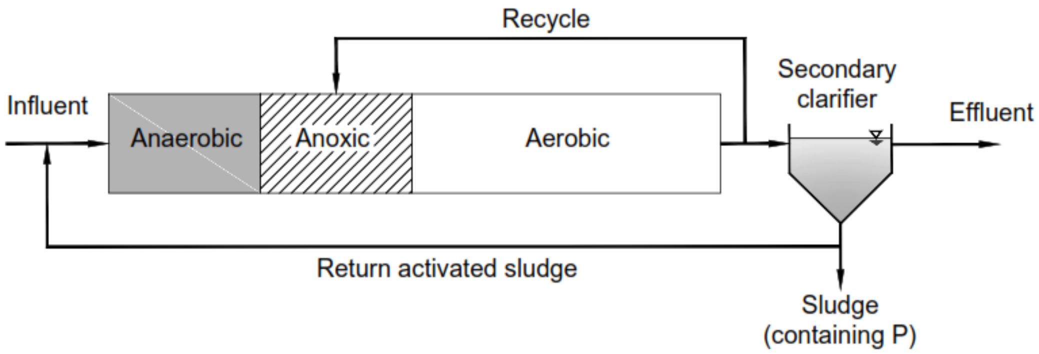

Figure 2-10 The Diagram of A2O Process Adapted from Figure 8-29 (b) (Stensel et al., 2014)

There are several commercial biological nutrient removal processes. Following A2O, 5-stage Bardenpho process is the most common among BNRs. There are also other configurations which are University of Cape Town (UCT), Virginia Initiative Plant (VIP) and Johannesburg processes (Moran, 2018; Stensel et al., 2014). The schematic diagrams of these processes are given in the following figures (Figure 2-11 to Figure 2-13). Typical design parameters for commonly used BNR processes are given in Table 2-2.

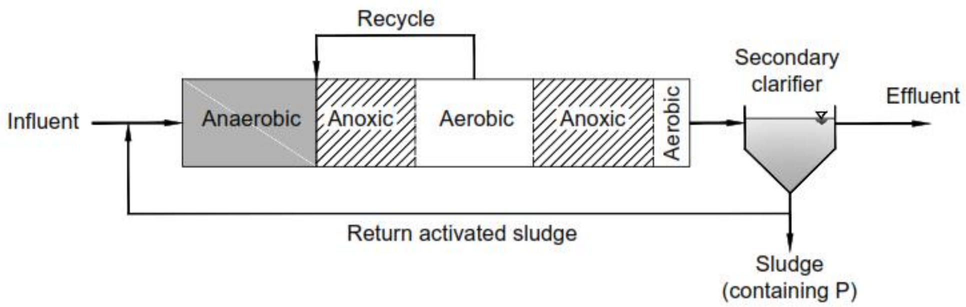

Figure 2-11 The Diagram of 5-Stage Bardenpho Process Adapted from Figure 8-29 (c) (Stensel et al., 2014)

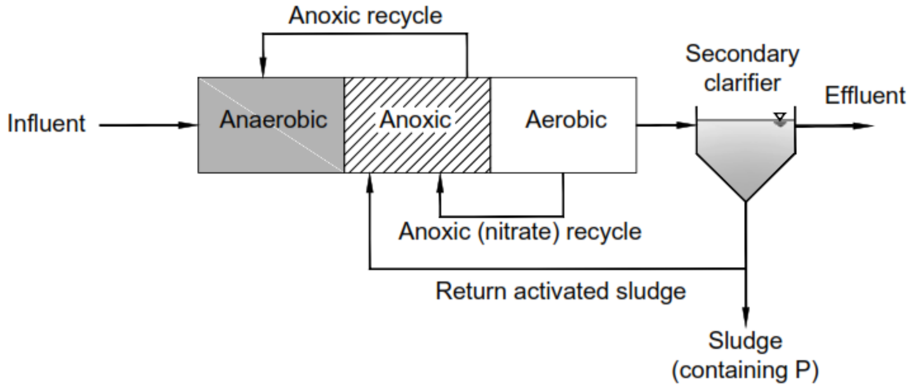

Figure 2-12 The Diagram UCT Process Adapted from Figure 8-29 (d) (Stensel et al., 2014)

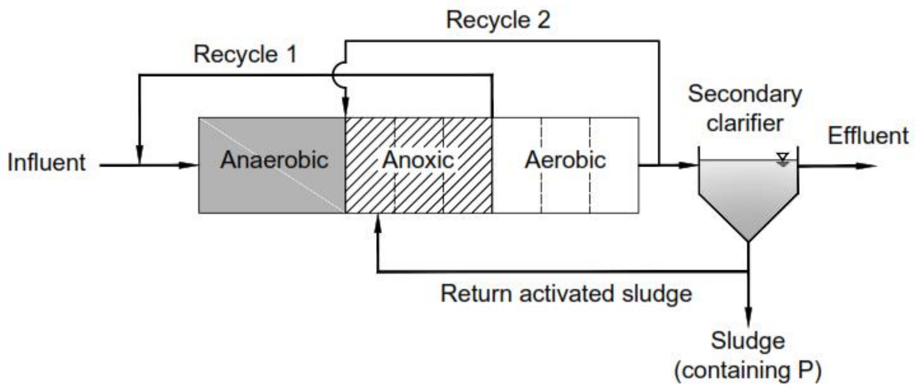

Figure 2-13 The Diagram of VIP Process Adapted from Figure 8-29 (e) (Stensel et al., 2014)

Table 2-2 Typical Design Parameters for Commonly Used Biological Nutrient Removal Processes Adapted from Table 8-26 (Stensel et al., 2014)

Design Parametre / Process	SRT (days)	MLSS (mg/L)	HRT (h)			RAS (% of influent)	Internal Recycle (% of influent)
			Anaerobic Zone	Anoxic Zone	Aerobic Zone		
A/O	2-5	3,000-4,000	0.5-1.5	-	1-3	25-100	-
A2O	5-25	3,000-4,000	0.5-1.5	0.5-1	4-8	25-100	100-400
Bardenpho-5	10-20	3,000-4,000	0.5-1.5	1-3 / 1-4	4-12 / 0.5-1	50-100	200-400
UCT	10-25	3,000-4,000	1-2	2-4	4-12	80-100	200-400
VIP	5-10	2,000-4,000	1-2	1-2	4-6	80-100	100-200

2.1.6. Sludge Stabilization

Some of the activated sludge should be removed from the treatment system and discharged. This sludge is called the waste activated sludge (WAS). This sludge contains microorganisms, organics, inorganic chemicals and metals. WAS quantity and solid concentration vary according to the treatment technology and the incoming wastewater characteristics. Additionally, solids removed from primary sedimentation are known as primary sludge (PS). PS usually has a high concentration of solids and pathogenic microorganisms (Sanin et al., 2011).

Waste sludges remain active after removal from the system in terms of microbial activity. Therefore, waste sludges should be stabilized, except for the waste sludges that are sent to combustion or solid waste digestion. Sludge stability can be categorized into three terms (Sanin et al., 2011);

- Energy availability for biological metabolisms
- Odor and putrefaction
- Adversity of health and environment

Anaerobic digestion, aerobic digestion, lime stabilization, chemical fixation, heat stabilization and sludge combustion are examples of sludge stabilization methods. On the other hand, thickening components (before stabilization) and dewatering components (after stabilization) are auxiliary units of sludge stabilization. The purpose of these units is to control the volume and solid concentration of sludge (Sanin et al., 2011; Stensel et al., 2014). Typical sludge solids concentrations are provided in Table 2-3.

Table 2-3 Expected Solid Concentrations from Sludge Operators Adapted from Table 14-8 (Stensel et al., 2014)

Operation or Process	**Solids Concentration % Dry Solids**	
Sedimentation	Range	Typical
PS	5-9	6
PS + WAS	3-8	4
WAS (with PS)	0.5-1.5	0.8
WAS (without PS)	0.8-2.5	1.3
Anaerobic Digestion	Range	Typical
PS	2-5	4
PS+WAS	1.5-4	2.5
Aerobic Digestion	Range	Typical
PS	2.5-7	3.5
PS+WAS	1.5-4	2.5

2.2. Specific Energy Consumption of a WWTP

Considering treatment plants have different sizes and configurations, it is hard to form standards on energy consumption. Electrical Power Research Institute (EPRI) and Water Research Foundation (WRF) studied the electrical consumption of WWTPs (Pabi et al., 2013). In this study, it was clearly seen that treatment plants with lower treatment capacities use more energy to treat wastewater. The results of this study are shown in Table 2-4. Additionally, most of the electrical consumption in treatment plants occur in the aeration operation. The electrical consumption distribution of treatment plants is shown in Figure 2-14 (Pabi et al., 2013).

Table 2-4 Weighted Average Values for Wastewater System Parameters from Filtered Energy Star Dataset (Pabi et al., 2013)

Average Daily Flow Range (MGD)	Energy Use Intensity (kWh/MG)	Average Effluent BOD (mg/l)	Generating Electricity Onsite (%)
< 2	3,300	7.3	10
2 - 4	3,000	6.7	14
4 - 7	2,400	7.5	7
7 - 16	2,000	6.5	45
16 - 46	1,700	7.2	39
46 - 100	1,700	12.2	44
101 - 330	1,600	11.5	18

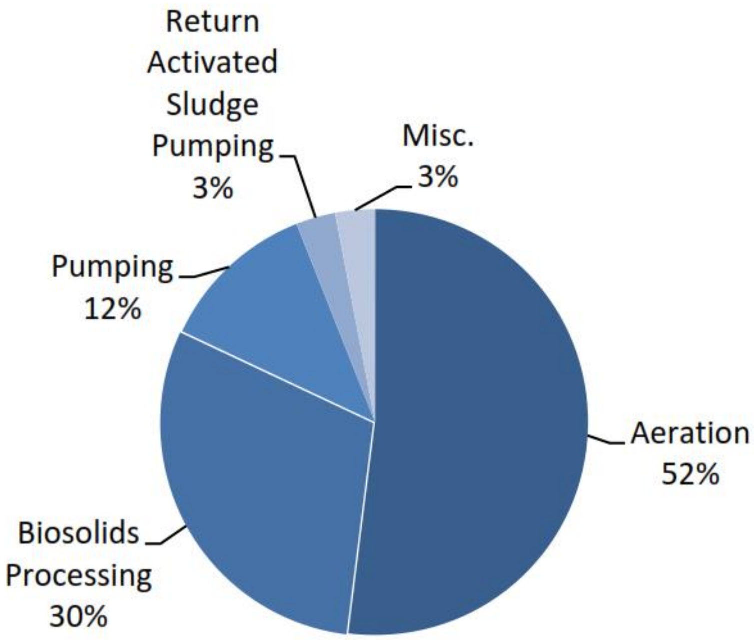

Figure 2-14 Typical Energy End-Uses in Municipal Wastewater Treatment (Pabi et al., 2013)

Many variables and factors are affecting the energy consumption of a municipal WWTP. In order to compare the energy consumptions of different treatment processes with different capacities, several methods have been developed. In literature, common energy key indicators are energy consumptions per volume of treated wastewater, per population equivalence (PE) and per $COD_{removed}$ (Longo et al., 2016). Since the PE differs from one country to another, it could be hard to compare specific energy consumptions of treatment plants from different countries using the PE indicator. On the other hand, specific energy consumptions per volume of treated water and COD removed values are comparable between countries.

In the literature, it can be found that energy consumption for 1 m^3 of treated wastewater ranges from 0.1 kWh/m^3 to 2.5 kWh/m^3 (Silva et al., 2015). This value mostly depends on treatment technology. It also varies between countries. Energy consumptions per treated wastewater volumes in different countries are given below in Figure 2-15.

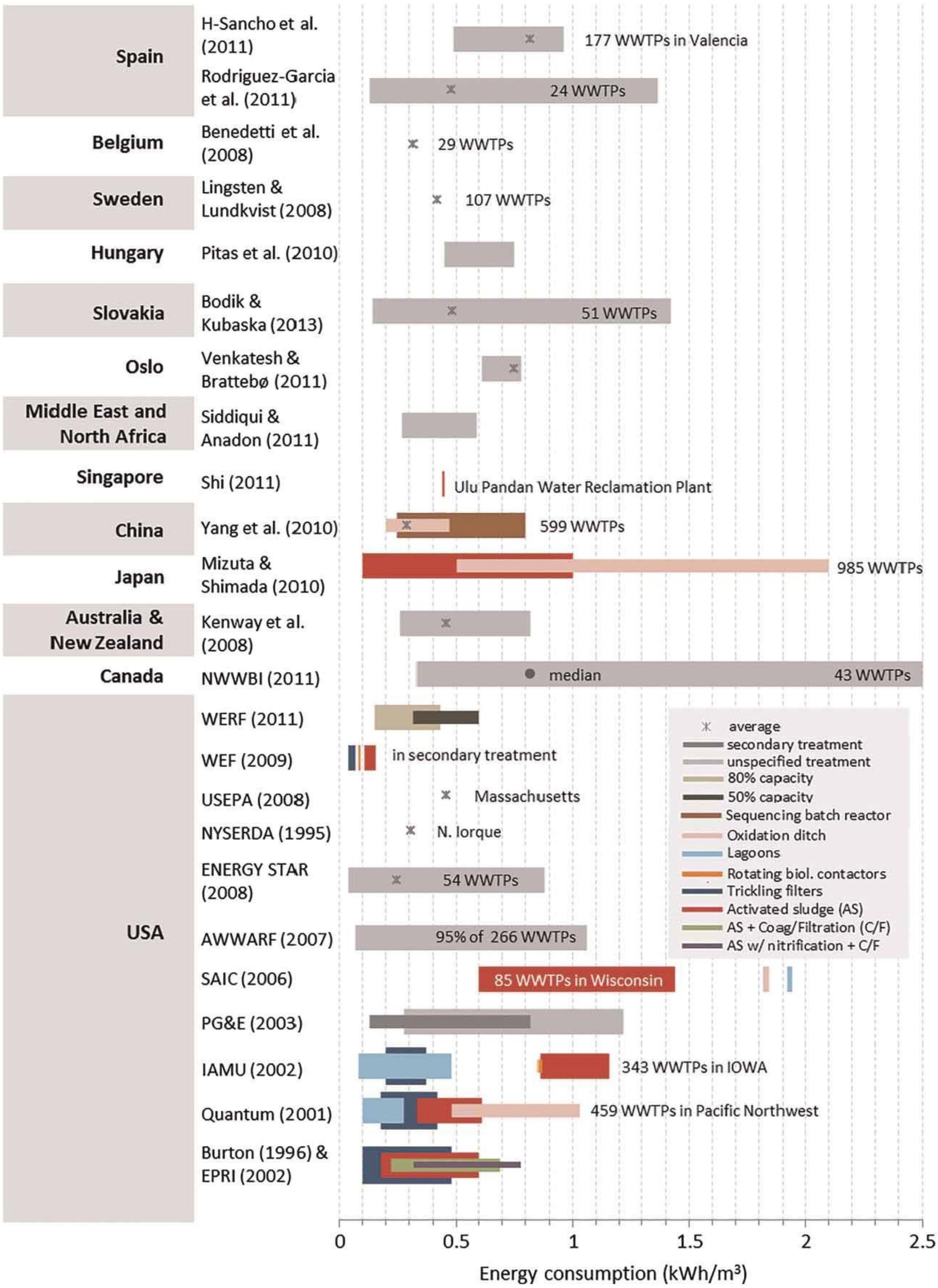

Figure 2-15 Energy Consumption per Treated Wastewater Volume in Different Countries (Silva et al., 2015)

2.3. Carbon Footprint of a Treatment Plant

In literature studies, a carbon footprint evaluation of a WWTP is usually done using life cycle assessment (LCA) (Mannina et al., 2019). Evaluations are site-specific. Although there is no official guideline for GHG emission control and modeling, the European Environment Agency (EEA) presented the EU climate and energy package (EEA, 2014). This package of legislation sets climate and energy targets for 2020. At the wastewater treatment sector level, there are three national targets, which are national government, national water utility association and local authority levels. Moreover, according to EEA Technical report No 5/2014, water and energy policies strongly affect the climate (EEA, 2014). This package can be considered as a start of GHG emissions legislation for the water sector at the national and municipal levels.

Calculating GHG emissions of domestic WWTP is challenging due to the lack of control and monitoring over emissions in treatment plant sites. In order to calculate GHG emissions of a treatment plant, the significant sources should results. GHGs are also generated during electricity production. For this matter, the total electricity consumption of a treatment plant should also be calculated. In literature, the GHGs emitted from WWTPs are named as direct emissions or on-site emissions. On the other hand, the GHGs arising from electricity production that is consumed in the plant are referred to indirect emissions or off-site emissions (Ashrafi et al., 2014).

The electricity production of a country should be investigated to understand the impact of WWTPs on indirect emissions that contribute to the carbon footprint. Electricity production in Turkey mainly depends on coal, with a percentage of 37.3%, followed by natural gas with 29.8%. Turkey provides 31.5% of its energy generation from renewable sources such as hydropower (19.8%), wind power (6.6%), solar power (2.6%) and geothermal energy (2.5%). The carbon equivalent emission of a conventional coal-burning power plant is approximately 1,000 gCO_2eq/kWh (POSTNOTE, 2006). Another fossil fuel-based, natural gas-powered electricity generation has 500 gCO_2eq/kWh carbon equivalent emission. This value seems preferable compared to coal-based power. However, renewable energy sources have a relatively low carbon footprint as compared to fossil fuels; hydropower has 10-30 gCO_2eq/kWh, wind energy has five gCO_2eq/kWh, solar power has 35 gCO_2eq/kWh carbon equivalent emission (POSTNOTE, 2006). With this information, the weighted carbon equivalent emission of electricity production in Turkey can be calculated as 540 gCO_2eq/kWh. Carbon footprint resulting from electricity production that is used to run a WWTP can be considered in determination of the overall carbon footprint. Moreover, carbon emissions during sludge transportation to final management sites can also be taken into consideration (EEA, 2017).

Literature studies show that direct GHG emissions have the largest contribution to the carbon footprint of a WWTP, which is between 40 to 70 % of the total (Delre et al., 2019). The quantity of N_2O gas emissions is lower than that of CH_4 and CO_2. However, since global warming potential (GWP) of N_2O gas is 265 times higher than CO_2, N_2O is deemed as the most significant contributor to direct GHG emissions. Studies also show that N_2O emission influencers such as $rbCOD_{in}/TKN_{in}$, SRT, IR have a significant effect on total GHG emissions. When $rbCOD_{in}/TKN_{in}$ increases from 0.65 to 1.25, N_2O reduction rate increases from 0.036 mg/min to 0.04 mg/min (Massara et al., 2017). On the other hand, when the temperature of wastewater decreases, it is reported that N_2O emission increase from 13% to 40% with the temperature decrease from 20°C to 10°C (Massara et al., 2017). Besides, enrichment of ammonium oxidizing bacteria (AOB) in wastewater favors N_2O emissions (Mannina et al., 2019). Previous studies also show that in BNR systems, N_2O emissions decrease with the increase in nitrogen removal (Massara et al., 2017).

2.4. WWTP Modeling

Since the treatment efficiencies and energy consumptions of wastewater treatment schemes vary considerably (Figure 2-15), predictions on treatment outcomes may be required. Conventional treatment cannot be considered sustainable for all cases. As seen in the literature, simulation-based approaches can aid the management and design of sustainable wastewater treatment and resource recovery (Khiewwijit et al., 2015).

In earlier stages of WWTP modeling, numerical methods were used. In 1983, the International Association on Water Quality (IAWQ), which is called International Water Association (IWA) started to study with a group of people on development of a WWTP model (Henze et al., 2017). Their main focus was to create a simple mathematical model that would provide accurate results. IAWQ aimed to achieve two primary goals. The first one was to improve the existing mathematical models concerning the accuracy and speed of convergence. The second goal was to use the model on single sludge systems (Henze et al., 2017). In 1987, Activated Sludge Model No 1 (ASM1) was presented (Henze et al., 1983). ASM2 followed the first model for better phosphorus removal predictions. These two models became standard tools for modeling biological removal at WWTPs. At the 8th World Congress on Anaerobic Digestion (1997), IWA nominated a group of people to study an anaerobic digestion model. In 2002 IWA published ADM1 (Batstone et al., 2002; Henze et al., 2017).

Today's computer models can analyze treatment plants using various operational parameters to develop a better strategy (Elawwad, 2018). Models can be used to predict the feasibility of untraditional configurations such as black water source separation (Tervahauta et al., 2013), microalgae biofilm water treatment (Boelee et al., 2012), urban water systems (Agudelo-Vera et al., 2012), etc. Moreover, simulation approach studies are available for both benchmarking of existing plants (Abusam et al., 2001) and feasibility studies based on simulations for new treatment options (Khiewwijit et al., 2015).

2.5. BioWin Simulation Software

In this study, *BioWin 5.3* computer package was used to simulate WWTP scenarios. BioWin is a software that can simulate wastewater treatment processes at steady-state and dynamic conditions. The software is an integration of ASM, ADM and a solid precipitation model (Katić, 2016). The developer of the software is Envirosim Associates Ltd. (Canada).

2.5.1. Process and Module Descriptions

The BioWin activated sludge/anaerobic digestion model (ASDM) contains more than fifty state variables and eighty process expressions (Envirosim, 2017). The typical biological processes occurring in the WWTP are simulated and the overall model contains;

- Activated Sludge Processes
- Anaerobic Digestion Processes
- Chemical Precipitation Reactions
- pH and Alkalinity Model

Activated Sludge Processes

The activated sludge (AS) processes in BioWin includes following modules;

<u>Growth and Decay of Ordinary Heterotrophic Organisms (OHOs)</u>

- Number of Processes: 24
- Objective: BOD removal, denitrification

The growth and decay of OHOs are described in this process group. A maximum specific growth rate, heterotrophic biomass concentration and Monod expression are used to calculate the growth. Under anoxic conditions the growth rate is multiplied with an anoxic growth factor. The default kinetic and stoichiometric parameters of

OHOs are provided in Table 2 5 and Table 2 6. pH inhibition and switching function parameters for OHOs can be seen in the BioWin manual (Envirosim, 2017).

Table 2-5 Kinetic Parameters of Ordinary Heterotrophic Organisms (OHOs) (Envirosim, 2017)

Name	**Default**	**Unit**
Max. spec. growth rate	3.2	d-1
Substrate half sat.	5	mgCOD/L
Anoxic growth factor	0.5	-
Denite N_2 producers (NO_3 or NO_2)	0.5	-
Aerobic decay rate	0.62	d-1
Anoxic decay rate	0.233	d-1
Anaerobic decay rate	0.131	d-1
Fermentation rate	1.6	d-1
Fermentation half sat.	5	mgCOD/L
Fermentation growth	0. 25	-
Free Nitrous acid	1.00E-	mol N /L

Table 2-6 Stoichiometric Parameters of OHOs (Envirosim, 2017)

Name	Default	Unit
Yield (Aerobic)	0.666	mgCOD/mgCOD
Yield (fermentation low H_2)	0.1	mgCOD/mgCOD
Yield (fermentation high H_2)	0.1	mgCOD/mgCOD
H_2 yield (fermentation low H_2)	0.35	mgCOD/mgCOD
H_2 yield (fermentation high H_2)	0	mgCOD/mgCOD
Propionate yield (fermentation low H_2)	0	mgCOD/mgCOD
Propionate yield	0.7	mgCOD/mgCOD
CO_2 yield (fermentation low H_2)	0.7	mmolCO2/mmolHAC
CO_2 yield (fermentation low H_2)	0	mmolCO2/mmolHAC
N in Biomass	0.07	mgN/mgCOD
P in Biomass	0.022	mgP/mgCOD
Endogenous fraction - aerobic	0.08	-
Endogenous fraction - anoxic	0.103	-
Endogenous fraction - anaerobic	0.184	-
COD:VSS Ratio	1.42	mgCOD/mgVSS
Yield (anoxic)	0.54	mgCOD/mgCOD
Yield propionic (anoxic)	0.64	mgCOD/mgCOD
Yield propionic (anoxic)	0.46	mgCOD/mgCOD
Yield acetic (aerobic)	0.6	mgCOD/mgCOD
Yield acetic (anoxic)	0.43	mgCOD/mgCOD
Yield methanol (Aerobic)	0.5	mgCOD/mgCOD
Max fraction to N_2O at high FNA over nitrate	0.05	mgN/mgN
Max fraction to N_2O at high FNA	0.1	mgN/mgN
Biomass volatile fraction (VSS/TSS)	0.92	mgVSS/ mgTSS
Endogenous residue volatile fraction (VSS/TSS)	0.92	mgVSS/ mgTSS
N in endogenous residue	0.07	mgN/ mgCOD
P in endogenous residue	0.022	mgP/ mgCOD
Endogenous residue COD:VSS Ratio	1.42	mgCOD/mgVSS
Particulate substrate COD:VSS Ratio	1.6	mgCOD/mgVSS
Particulate inert COD:VSS Ratio	1.6	mgCOD/mgVSS

Growth and Decay of Methylotrophs

- Number of Processes: 6
- Objective: denitrification using methanol

In BioWin model, the growth and decay of heterotrophs using methanol under anoxic conditions were described with these processes. Model's methylotrophs can only grow under anoxic conditions using methanol as the substrate with nitrate or nitrite as the electron acceptor. There is a minimum "anoxic SRT" to protect these microorganisms from washing out from the activated sludge system. Maximum specific growth rate, anoxic methylotrophs concentration and a Monod expression are used to calculate the growth rate. Model parameters are provided in the manual (Envirosim, 2017).

Hydrolysis, Adsorption, Ammonification and Assimilative denitrification

- Number of Processes: 10
- Objective: Conversion of organics, nitrogen and phosphorus fractions

In this module, hydrolysis of biodegradable particulate organic substrate to readily biodegradable complex substrate and biodegradable particulate organic nitrogen and phosphorus are described. Moreover, adsorption or flocculation of colloidal organic material, ammonification of soluble organic nitrogen, assimilative denitrification of nitrate or nitrite and slow decay of endogenous products are also defined with this module. These processes are described separately from microorganism groups due to different microorganism types. Model parameters are provided in BioWin Manual (Envirosim, 2017).

Growth and Decay of Ammonia Oxidizing Biomass (AOB)

- Number of Processes: 4
- Objective: Nitrification

This biomass uses the energy to synthesize organic material from inorganic carbon and grows by oxidizing ammonia. The growth rate of the biomass is calculated by using maximum specific growth rate, biomass concentration and a Monod expression. The growth rate is also modified with dissolved oxygen (DO), nutrient concentration and pH inhibition. Model parameters are provided in BioWin manual (Envirosim, 2017).

Growth and Decay of Nitrite Oxidizing Biomass (NOB)

- Number of Processes: 2
- Objective: Nitrification

This biomass uses the energy to synthesize organic material from inorganic carbon and grows by oxidizing nitrite to nitrate. Ammonia is the nitrogen source for these microorganisms. The biomass growth rate is calculated by using the maximum specific growth rate, the nitrite-oxidizing biomass concentration and a Monod expression for nitrite. The base rate is modified with DO and nutrient concentration and pH inhibition. Model parameters are provided in BioWin manual (Envirosim, 2017).

Growth and Decay of Anaerobic Ammonia Oxidizers (AAO)

- Number of Processes: 2
- Objective: Nitrification

This biomass uses the energy to synthesize organic material from inorganic carbon and grows by converting ammonia and nitrite to nitrogen gas and nitrate. The biomass growth rate is a product of the maximum specific growth rate, the AAO concentration, a Monod expression for ammonia and a Monod expression for nitrite. Model parameters are provided in BioWin manual (Envirosim, 2017).

Growth and Decay of Phosphorus Accumulating Organisms (PAOs)

- Number of Processes: 17
- Engineering Objective: Biological phosphorus removal
- Implementation: Permanent

The module describes the growth and decay of polyphosphate accumulating organisms (PAOs). The PAOs use polyphosphate as an energy source and sequester volatile fatty acids (VFAs) under anaerobic conditions. Sequestration rate is a product of the sequestration rate constant, the PAO concentration and a Monod switch on the appropriate substrate. Under P limited conditions, the model uses a different growth rate constant. The base growth rate is calculated by using the maximum specific rate constant, the PAO concentration and a Monod switch on the ratio polyhydroxyalkanoates (PHA) to PAOs. Model parameters are provided in BioWin manual (Envirosim, 2017).

Anaerobic Digestion Processes

Anaerobic digestion model contains the following modules;

Heterotrophic Growth through Fermentation

- Number of Processes: 2
- Objective: VFA generation (fermenters, digesters)

The anaerobic growth factor is calculated using the maximum specific growth rate constant, the heterotrophic biomass concentration and a Monod expression for the substrate. The rate is modified by nutrient limitations and pH inhibition. The decay rate varies according to the electron acceptor of the environment. The model parameters are provided in BioWin manual (Envirosim, 2017).

Growth and Decay of Propionic Acetogens

- Number of Processes: 2
- Objective: anaerobic digestion

The module describes the growth and decay of propionic acetogenins. The rate expression is a product of the maximum specific growth rate, the propionic acetogenins concentration and a Monod expression for propionate. The growth rate is modified with environmental conditions (hydrogen and acetate), nutrient limitations and pH inhibition. The model parameters are provided in BioWin manual (Envirosim, 2017).

Growth and Decay of Methanogens

- Number of Processes: 6
- Objective: anaerobic digestion

The module describes the growth and decay of methanogens converting acetate and hydrogenotrophic methanogens converting CO_2. The growth rate expression is a product of the maximum specific growth rate, the biomass concentration and a Monod expression for each of the substrates. The rate is also modified with nutrient limitation and pH inhibition. The parameters are provided in BioWin manual (Envirosim, 2017).

Chemical Precipitation Reactions

The model contains the following modules;

Ferric or Alum Precipitation

- Number of Reactions: 6
- Objective: Chemical phosphorus removal

The model is selected as an option from *"Model Options"* and its use is optional. The model equation is expressed by using an equilibrium approach. The added metal can be selected as Ferric or Alum. The metal addition forms soluble metal-phosphate and insoluble phosphate/hydroxo complexes. The equilibrium is affected by pH of the medium. The parameters are provided in BioWin manual (Envirosim, 2017).

<u>Struvite and Calcium Phosphates Precipitation</u>

- Number of Processes: 3
- Objective: Formation of Struvite and Calcium Phosphates

The model is selected as an option from "*Model Options*" and its use is optional. In wastewaters, magnesium and calcium can form precipitation as struvite or hydroxy-dicalcium-phosphate (HDP). Besides HDP, BioWin contains one more calcium phosphate precipitate, hydroxyapatite (HAP). The model parameters are provided in BioWin manual (Envirosim, 2017).

pH and Alkalinity Model

The implementation of this model is optional. The pH model is based on the equilibrium of phosphate, carbonate, ammonium, VFA systems and typical strong ions in wastewater. Alkalinity is estimated with pH model using ionic species at the current system state. The description of the model is provided in BioWin Manual (Envirosim, 2017).

2.5.2. Interface and Solver Descriptions

BioWin software uses a drawing board to visualize the treatment plant components. Also, component-specific windows allow users to specify physical and operational data for that component. The key calculation features of the software can be illustrated as; energy consumption and operating costs, blower and surface aerators power, onsite power generation, heat recovery, comprehensive pH, chemical and biological P removal, struvite precipitation, treatment efficiencies, effluent characteristics, etc. A demonstration of the BioWin interface is given in Figure 2-16.

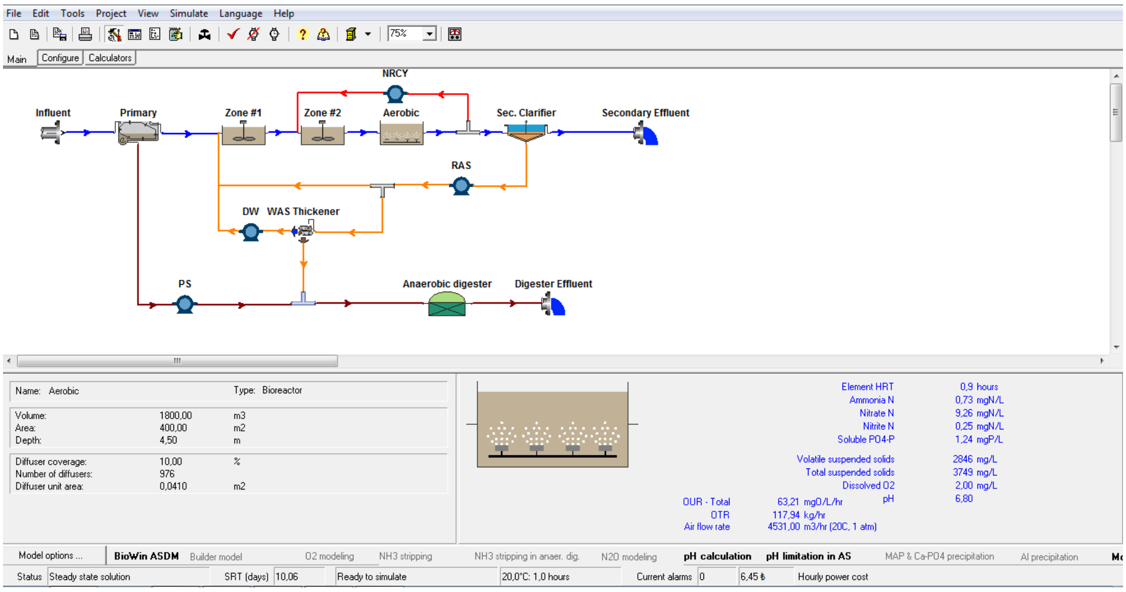

Figure 2-16 Demonstration of BioWin Software Interface

BioWin simulator can solve the mass balance of a system for both steady-state and dynamic conditions. The steady-state module is used to analyze systems based on constant flow and loadings while the dynamic simulator is used to analyze systems with time-varying inputs (Envirosim, 2017).

Solver modules of BioWin software use *"The BioWin Hybrid Method"* which is a combination of the Newton-Raphson (NR) (second-order) Search and a Decoupled Linear Search (DLS) (Envirosim, 2017). The hybrid method selects the best approach for the model and switch between them if it is necessary. On the other hand, the user can also select the method manually. The default maximum allowable error is 0.1%. The maximum allowable error can be defined by user to increase simulation speed (Envirosim, 2017).

In BioWin software, the integrated ASDM model is used as a default for all biological unit processes. Models for ammonia stripping, nitrous oxide production, pH calculations, chemical precipitation can also be opened and closed by user (Envirosim, 2017).

Various treatment operators can be simulated in BioWin software. These operators include (Envirosim, 2017);

- AS bioreactors
- SBRs
- Media reactors (IFAS)
- MBBR systems
- Anaerobic or aerobic digesters
- Settling tank modules
- Influent elements such as wastewater, metal, chemical, methanol
- Auxiliary modules such as flow splitters and combiners, equalization tanks, thickening and dewatering units

In literature, it can be observed that BioWin software was used in studies such as WWTP simulation (Dursun et al., 2011; Elawwad et al., 2016), sensitivity analysis (Dursun et al., 2011), optimization studies (Elawwad, 2018; Elawwad et al., 2019), respirometric and titrimetric measurements (Sin et al., 2007), design improvement strategies (Katić, 2016).

CHAPTER 3

COMPARISON OF DIFFERENT TREATMENT SCHEMES BASED ON SLUDGE PRODUCTION AND REMOVAL EFFICIENCY FOR MUNICIPAL WWTPS

3.1. Introduction

Municipal wastewater generation is increasing with residential and industrial activities. Surface waters are getting more polluted with domestic, industrial and agricultural wastes. However, WWTPs are located in only 296 of 1,397 municipalities of Turkey (TUIK, 2016a). Contaminated water resources not only affect biodiversity, but also many people whose livelihoods depend on water. Buyuk Menderes River, Egirdir Lake, Bafa Lake, Salt Lake, Gediz Delta, Uluabat Lake, Beyşehir Lake, Eber Lake, Burdur Lake, and Göksu Delta are only a few of the wetlands affected by pollution (Öktem et al., 2014).

In our country, The Ministry of Environment and Urbanization declared the 2023 wastewater action plan (T.C. Çevre ve Şehircilik Bakanlığı, 2016). According to the wastewater action plan, 1,501 WWTPs will be built by 2023. At the moment, 906 municipal WWTPs are being operated in Turkey. On the other hand, there are 81 municipal WWTPs under construction (T.C. Çevre ve Şehircilik Bakanlığı, 2018).

Collecting and treating the wastewater in WWTPs results in sludge production which should be well managed. This sludge could be stabilized in the treatment plant with the help of aerobic or anaerobic digesters for better management. However, in Turkey, only 24% of the treatment plants are stabilizing their waste sludges (T.C. Çevre ve Şehircilik Bakanlığı, 2015). Due to the high calorific value of sewage sludge, thermal conversion methods such as combustion, gasification and pyrolysis, appear to be more promising than landfill application for the fate of waste sludges in sustainable management. Yet, sewage sludges are also nutrient-rich organic substances. This attribute is still making waste sludges usable for land applications (Werle, 2015). Turkey's Ministry of Environment and Urbanization is preparing an action plan for treatment of sludges to achieve sustainable management. With the collaboration of Middle East Technical University, Action Plan is expected to be released in late 2019 (B2B Medya, 2018).

With increasing capacity and quantity requirements of WWTPs, the selection of the most appropriate treatment process for urban WWTP design becomes a growing problem. With these requirements, existing treatment plants force to utilize their operators fully and restrict them financially (Khiewwijit et al., 2015). As a consequence, the construction of an effective and appropriate treatment plan scheme for the observed influent and desired effluent characteristics is a problem that has been studied in many techniques (Commonwealth, 2004). In the literature, WWTP modeling is also used to select treatment plant operations and improve plant efficiency (Yin et al., 2018). However, in our country, wastewater treatment system identification problem is a difficult task primarily when the system is not modeled in the design stage. In addition to that, there are some urban WWTPs that do not work effectively in Turkey (Türkmenler, 2017). It could be deducted that new academic approaches seem to have difficulty integrating into practice.

In this context, instead of proposing new methods for water treatment plants in Turkey, a modeling study was carried out for the existing plants and the more efficient operation and scheme building of these plants. This study aims to compare treatment efficiencies and sludge production amounts in municipal WWTP schemes commonly used in Turkey via BioWin simulations. This study would provide numerical waste sludge analysis, removal efficiency assessment and conceptional pros/cons of Turkey's most used treatment plant schemes for different influent characteristics.

3.2. Methodology

In this study, Turkey's widely used wastewater treatment schemes were analyzed and simulation model were created in order to compare the removal efficiencies and sludge production rates for different treatment technologies. All treatment plant models were kept in the same flow capacity. Three different influent characteristics and one effluent target were chosen to design all models. 35 combinations of treatment schemes were prepared. With three different influent characteristics, a total of 105 models were prepared and run in this study.

The methodology consists of the following steps; i) selection of flowrate ii) selection of wastewater characteristics iii) identification of scheme operators iv) determination of effluent target v) modeling approach. The purpose of this procedure is to generate comparable treatment scheme models. For this study, BioWin 5.3 software was used for model building.

3.2.1. Selection of Flowrate

In this initial step, Turkey's urban WWTPs' capacity comparison was made to select the operational flowrate of the models. For capacity comparison, "The Management Of Domestic/Urban Sewage Sludge Project" is used (T.C. Çevre ve Şehircilik Bakanlığı, 2015). In that study, 232 existing treatment plants were investigated in terms of flowrate capacity of the WWTPs. The smallest and the biggest flowrate capacities are stated as 5.7 m^3/day and 765,000 m^3/day respectively. The total capacity of these treatment plants was calculated as 8,069,981 m^3/day. Therefore, it can be said that at least 8 million m^3 of wastewater are being processed daily in these WWTPs. Median and average values of daily capacities of the treatment plants were calculated as 6,836 m^3/day and 34,784 m^3/day. It can be stated that 50% of the treatment plants have a smaller capacity than 7,000 m^3/day.

In order to understand the capacity distribution of these treatment plants, a graphical histogram approach was performed with four different flowrates. These flowrates are 15,000, 35,000, 100,000 and 250,000 m^3/day. In Figure 3-1, the number of treatment plants for different capacities is provided in the histogram graph. A histogram graph by total wastewater processed is also provided in Figure 3-2.

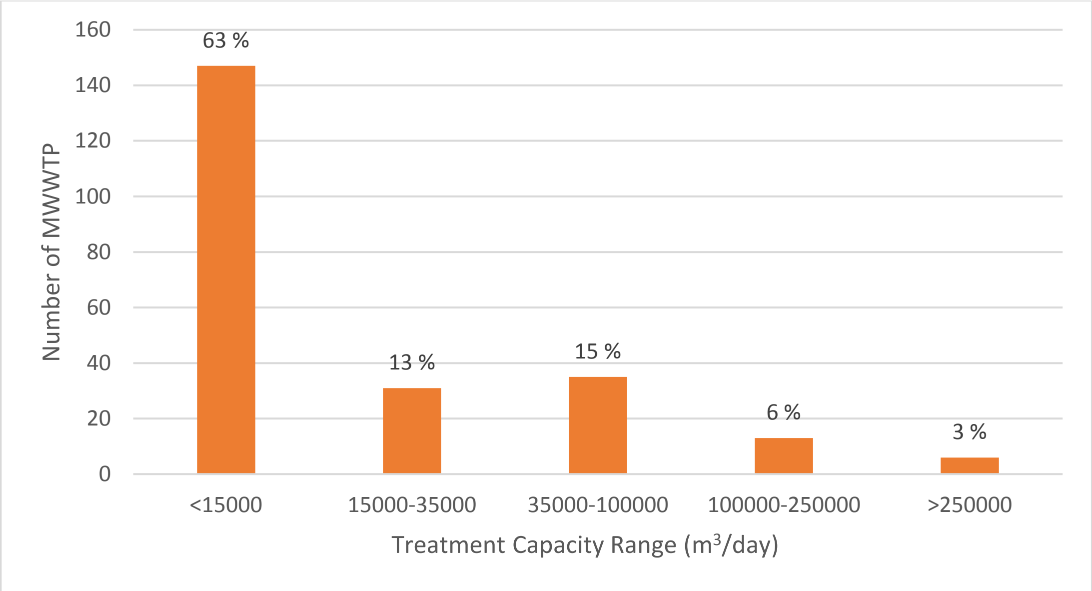

Figure 3-1 Number of Municipal WWTPs Histogram Distribution of Turkey by Treatment Plant Capacity (T.C. Çevre ve Şehircilik Bakanlığı, 2015)

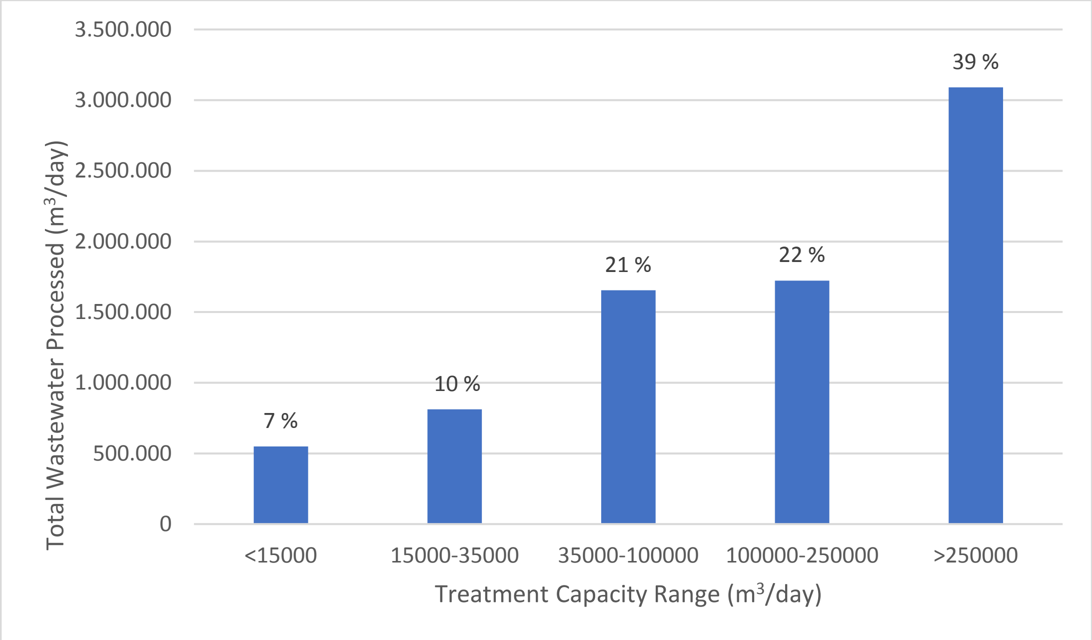

Figure 3-2 Processed Wastewater Histogram Distribution of Turkey by Treatment Plant Capacities (T.C. Çevre ve Şehircilik Bakanlığı, 2015)

It can be stated that 61% of the treatment plants have a lower capacity of 15,000 m^3/day. However, in these facilities, only 7% of the total of 8 million m^3 wastewater is processed daily. In Figure 3-2, it can be seen that the treatment plants having a capacity greater than 100,000 m^3/day are processing 61% of the total wastewater amount. It can be deducted that sludge produced in treatment plants with a capacity of more than 100,000 m^3/day constitutes the majority of the total wastewater processed and the sludge produced. Therefore, the single flow rate to be used in models was selected as 100,000 m^3/day.

3.2.2. Selection of Wastewater Characteristics

Raw municipal wastewater consists mostly of water with suspended and dissolved organic and inorganic solids with relatively small concentrations (Stensel et al., 2014). Table 3-1 shows the typical concentrations of the main components of low, medium, and high strength domestic raw wastewater (Stensel et al., 2014). All three strengths were selected to be used in the study.

Table 3-1 Composition of Wastewater for Different Strengths (Stensel et al., 2014)

Constituents	**Concentrations (mg/L)**		
	Low strength WW	**Medium strength WW**	**High strength WW**
BOD_5	110	190	350
COD	250	430	800
TSS	120	210	400
NH_3-N	12	25	45
Organic-N	8	15	25
TKN	20	40	70
Organic-P	1	2	4
Inorganic-P	3	5	8
Oil & grease	50	90	100

3.2.3. Identification of Scheme Operators

In this step, the selection of the biological treatment and sludge treatment processes for the models will be explained. The biological treatment units and the sludge treatment process types to be used in the model study were selected considering the most used municipal WWTP processes in Turkey. To this purpose, the management of domestic/urban sewage sludge project which was presented by the Ministry of Environment and Urbanization was used (T.C. Çevre ve Şehircilik Bakanlığı, 2015). In this project, the existing facilities were examined in detail. Project results revealed that the most commonly used biological treatment technologies (processes) in Turkey are conventional AS (CAS) process, BNR processes such as Bardenpho5 and A2O, and extended aeration process (Figure 3-3). 35% of all biological treatment units in Turkey have a CAS process. On the other hand, BNR systems and extended aeration processes cover 44% and 15% of all biological treatment units, respectively. The rest of the treatment plants are trickling filters, ponds and MBR systems. When the BNR distribution is analyzed, it is seen that 52% of the BNRs are A2O, 40% is Bardenpho and 5% is AO processes. Therefore, A2O is the most commonly used BNR type in Turkey (Figure 3-4).

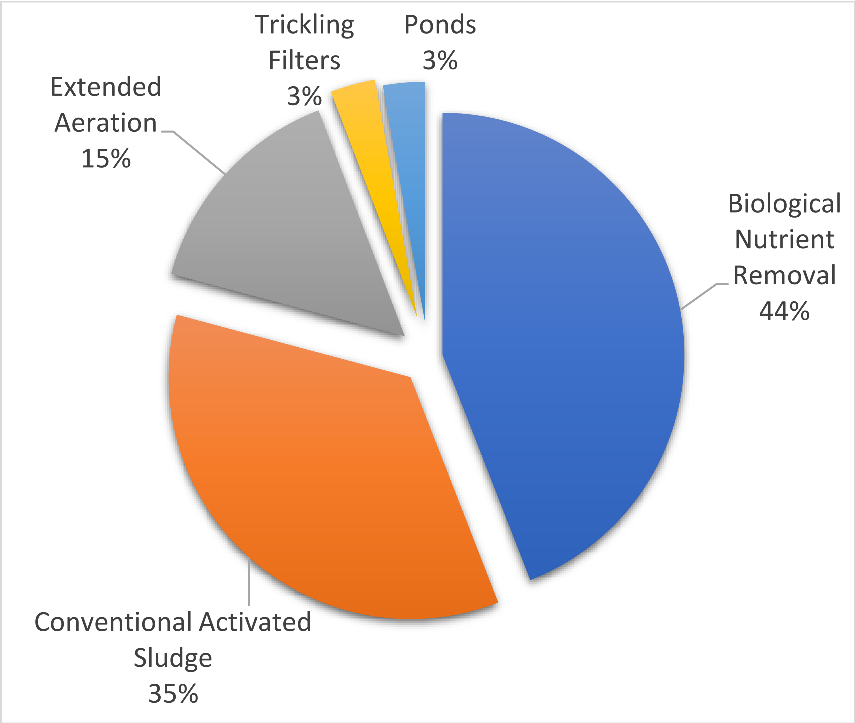

Figure 3-3 Distribution of Biological Treatment Systems in Municipal and Domestic WWTPs of Turkey (T.C. Çevre ve Şehircilik Bakanlığı, 2015)

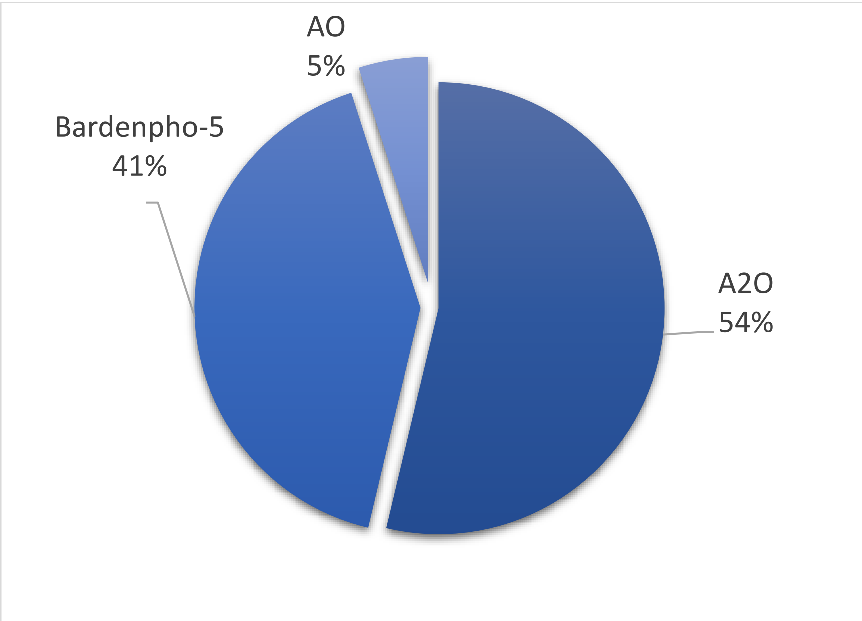

Figure 3-4 The Distribution of Biological Nutrient Removal (BNR) Unit Types in Turkey (T.C. Çevre ve Şehircilik Bakanlığı, 2015)

The project report also reveals that sludge stabilization is performed in only 25% of all WWTPs. The most commonly used sludge stabilization processes are aerobic digestion, anaerobic digestion, lime stabilization and composting. In Table 3-2, sludge stabilization processes are provided with their percent usages in Turkey (T.C. Çevre ve Şehircilik Bakanlığı, 2015).

Table 3-2 Sludge Stabilization Processes used in Turkey (T.C. Çevre ve Şehircilik Bakanlığı, 2015)

Sludge Stabilization	Availability (%)
Aerobic Digestion	53%
Anaerobic Digestion	29%
Lime Stabilization	16%
Composting	2%

Regarding the results of domestic/urban sewage sludge project of Turkey, the most preferred schemes for secondary treatment of model buildings were selected as conventional activated sludge process, extended aeration process, A/O process, A2O process and Bardenpho-5 process.

For extended aeration process, primary sedimentation is not used commonly (Stensel et al., 2014). Therefore, primary sedimentation is not placed in the models of the extended aeration process. On the other hand, in Turkey, it can be observed that in some of the WWTPs with A2O and Bardenpho-5 processes, primary sedimentation is being used. For example, Antalya City has two municipal WWTPs in the central districts. Both treatment plants are using Bardenho-5 processes. However, one of them is using primary sedimentation (ASAT, 2005); the other one does not have primary sedimentation (ASAT, 2011). To have a better understanding of primary sedimentation usage on A2O and Bardenpho-5 processes, two scenarios were taken into consideration separately as with and without primary sedimentation. To sum up, seven treatment options were selected.

On the other hand, five different sludge treatment processes were selected. Sludge treatment options could be listed as;

- No action
- Thickening and Dewatering
- Thickening, Aerobic Digestion and Dewatering
- Thickening, Anaerobic Digestion and Dewatering
- Thickening, Pre-Treatment, Anaerobic digestion and Dewatering

Thickening and dewatering can be stated as the default process according to domestic/urban sewage sludge project of Turkey. No action sludge treatment option was also discussed as a reference point for comparison of sludge treatment processes. In Turkey, only 25% of the urban WWTPs have a sludge stabilization unit. Most used sludge stabilization options, which are anaerobic digestion and aerobic digestion, were placed for sludge treatment options. Additional to anaerobic digestion (AD), thermal hydrolysis was selected for AD as a pre-treatment option. Numerous studies report that thermal hydrolysis enhances anaerobic digestion performance (Carrère et al., 2010). It was also stated that thermal hydrolysis led to a 20% increase in methane production of anaerobic digestion (Carrère et al., 2010).

As several process combinations were simulated for different wastewater strengths, a naming convention was used to distinguish between different cases named in the form S_X_Y_Z. Here S is composed of 2 letters representing the strength of the wastewater treated (Table 3-3). X is composed of two to four characters that express the treatment process used. Y is an array of 2 elements composed of numbers or characters. It points out whether sludge pre-treatment is used before sludge stabilization or not. Sludge pre-treatment was used only before anaerobic digestion. And, finally, Z stands for sludge processing options. It is composed of 3 characters or numbers. Definitions are provided in Table 3-3. To illustrate, MS_BD5S_TH_AND is the model in which the medium strength wastewater is treated by Bardenpho-5 process with primary sedimentation and resulting sludge is anaerobically digested with thermal hydrolysis pre-treatment. HS_EXT_00_001 is the high strength wastewater treated with extended aeration where the resulting sludge is thickened and dewatered only. Overall, using different combinations of wastewater characteristics, treatment methods and sludge handling, 105 different cases were considered.

Table 3-3 Codes in Naming Convention Used for Different Cases (S_X_Y_Z)

Code S	**Strength of Wastewater**
HS	High Strength
MS	Medium Strength
LS	Low Strength
Code X	**Treatment Processes**
CON	Conventional Activated Sludge
EXT	Extended Aeration
AO	A/O
A2O	A2O with no primary sedimentation
A2OS	A2O with primary sedimentation
BD5	Bardenpho-5 with no primary sedimentation
BD5S	Bardenpho-5 with primary sedimentation
Code Y	**Sludge pre-treatment before stabilization**
00	No sludge pre-treatment
TH	Thermal hydrolysis
Code Z	**Sludge processing**
000	No action
001	Thickening and dewatering
AED	Thickening, aerobic digestion and dewatering
AND	Thickening, anaerobic digestion and dewatering

3.2.4. Determination of Effluent Target

In this step, target effluent wastewater characteristics were determined. In order to set target effluents, selected flowrate's (100,000 m^3/day) serving population equivalence was calculated.

In Turkey, BOD generation per capita.day is 45-60 g/cap.day (T.C. Çevre ve Şehircilik Bakanlığı, 2004, 2014). Maximum and minimum BOD concentrations for selected influent wastewater characteristics can be stated as 350 and 110 mg/L for high and low strength wastewaters (Table 3-1). Therefore, the incoming BOD daily load of selected wastewater strengths could be between 35,000,000 g/day for high strength wastewaters and 11,000,000 g/day for low strength wastewaters. When incoming BOD daily load values are divided by BOD generation values of Turkey, the highest possible PE and lowest possible PE were calculated. PE results are 777,778 and 183,333 capita respectively. In Turkey's regulations, there are different discharge criteria for different PE values. These PE values are 2,000, 10,000 and 100,000 cap. Since the lowest possible calculated PE value is 183,333, effluent targets were selected for WWTPs that are serving for 100,000 PE or more. The BOD, COD and TSS effluent limits were taken from Table 21-4 of "Water Pollution Control Regulation", and the TN and TP effluent limits were taken from Table 2 of "Urban Wastewater Control Regulation" (T.C. Çevre ve Şehircilik Bakanlığı, 2004, 2014). The effluent limits taken from the regulations are provided in Table 3-4.

Table 3-4 Selected Effluent Limit Characteristics

Effluent Characteristics	**Effluent Limits (mg/L)**
BOD_5	35
COD	90
TSS	25
TN	10
TP	1

For all selected biological treatment options, BOD, COD and TSS effluent targets are achievable. On the other hand, models with nutrient removal technologies such as A2O (S_A2OS_Y_Z) and Bardenpho-5 (S_BD5_Y_Z & S_BD5S_Y_Z) processes are expected to meet TP and TN targets taken from "Urban Wastewater Treatment Regulation" for sensitive receiving body environment as well (T.C. Çevre ve Şehircilik Bakanlığı, 2014). Moreover, A/O (S_AO_Y_Z) process is also expected to meet TP target.

3.2.5. Modeling Approach

In the modeling phase, with the combination of wastewater and sludge treatment options, 35 different treatment schemes were created. All the schemes were modeled in BioWin environment and replicated three times for three different wastewater characteristics input.

Bioreactor sizing was done within the typical design parameters (Table 2-1, Table 2-2). In order to compare removal efficiencies of different sludge treatment options, sizing of the bioreactors was kept constant for a given strength of the wastewater and treatment options (for code S and X). On the other hand, SRT of each treatment option was kept constant regardless of the strength of the wastewater (for code X). Selected SRT values of wastewater treatment options are provided in Table 3-5. Design parameters of created models used in simulations for different cases are provided in Appendix A Table *A-1* to Table *A-7*. Moreover, process flow schemes used for different treatment methods and sludge handling options are provided in Appendix B Figure B-1 to Figure B-9.

Table 3-5 Selected SRT values for wastewater treatment technologies

Treatment Option	SRT (days)
Conventional AS	5
Extended Aeration	30
A/O	5
A2O	10
Bardenpho-5	15

The variables that were changed from default values can be listed as follows;

List of Assumptions

- Primary sedimentation underflow solid concentration is typically between 4 and 5.5% (Sanin et al., 2011; Stensel et al., 2014) Therefore, underflow rates were adjusted to operate at 45,000 mg/L TSS concentration.
- The surface over flowrate of secondary clarifiers was adjusted to operate between 16 to 32 m^3/m^2.day (Stensel et al., 2014).
- In conventional activated sludge and extended aeration system surface aerators were used. In BNR systems aeration with diffusers were used.
- Thickening and dewatering capture rates were changed to 90% from the default value of 100% (Sanin et al., 2011).
- Thickening underflow TSS concentration was fixed around 70,000 mg/L. On the other hand, for aerobic digestion scenarios, that value was fixed between 40,000-50,000 mg/L (Sanin et al., 2011).
- Waste sludge TSS concentration was kept above 22% (Sanin et al., 2011).
- In order to meet discharge standards, chemical addition was applied if necessary. Added chemicals were aluminum salt in secondary clarifiers to meet TP target in the discharge and calcium carbonate for pH control in aerobic digestion. In addition to that, struvite recovery was applied to AD sludge processes if necessary.

To sum up, 105 different BioWin model scheme combinations were created for comparison.

3.3. Results and Discussion

In this study, wastewater treatment and sludge treatment technologies used in Turkey were investigated and combined to create different scenarios that possibly have a real WWTP representation in Turkey. As a result, five different treatment options were selected to be used in models. These treatment options are conventional AS, extended aeration, A/O, A2O and bardenpho-5. Additionally, A2O and Bardenpho-5 treatment options were also considered with and without primary sedimentation. Therefore, the number of selected treatment option can be stated as seven in that consideration. For selected SRT values, operating MLSS and raw daily sludge production results of different wastewater treatment options without any sludge processing for three different influent strengths are provided in Table 3-6.

Table 3-6 SRT, MLSS and Sludge Production Values of the Models

Model Name	SRT (days)	Average MLSS (mg/L)	Sludge Production (kg/day)
HS_CON	5	3,219	37,328
MS_CON	5	3,539	19,026
LS_CON	5	3,071	10,614
HS_EXT	30	2,977	19,995
MS_EXT	30	2,051	10,313
LS_EXT	30	2,129	5,338
HS_AO	5	4,292	38,709
MS_AO	5	3,281	20,002
LS_AO	5	3,066	11,212
HS_A2OS	10	2,786	36,305
MS_A2OS	10	2,869	18,766
LS_A2OS	10	2,288	10,573
HS_BD5S	15	3,006	34,575
MS_BD5S	15	2,831	17,990
LS_BD5S	15	2,143	10,038
HS_A2O	10	3,496	27,999
MS_A2O	10	3,539	14,443
LS_A2O	10	3,071	7,833
HS_BD5	15	4,004	26,265
MS_BD5	15	3,860	13,477
LS_BD5	15	3,064	7,339

For sludge treatment options, besides only thickening and dewatering, three sludge stabilization methods were selected to use in models. These are aerobic digestion, anaerobic digestion and anaerobic digestion with thermal hydrolysis. No action for sludge treatment was also taken into consideration. Therefore, five different sludge treatment options were used to create models. In this context, 105 different wastewater treatment models were created in BioWin Models. Effluent results for each model are provided in Appendix C Table *C-1* to Table *C-7*. Waste sludge productions of the treatment schemes are provided in Table 3-7 and Figure 3-5. As clearly seen in Figure 3-5 as the strength of wastewater decreases, the amount of daily sludge produced decreases for the specific biological and sludge treatment unit, as expected.

Table 3-7 Waste Sludge Production of the Models

Sludge Treatment	**Waste Sludge Production (kg/day)**						
	Treatment Process (X)						
High Strength	**CON**	**EXT**	**AO**	**A2OS**	**BD5S**	**A2O**	**BD5**
HS_X_00_000	37,328	19,995	38,709	36,305	34,575	27,999	26,265
HS_X_00_001	36,658	19,487	38,090	35,347	33,853	27,037	25,639
HS_X_00_AED	21,966	16,977	24,464	24,132	23,029	21,752	20,786
HS_X_00_AND	18,976	17,048	21,956	16,579	16,074	16,729	16,025
HS_X_TH_AND	15,041	15,915	18,716	14,558	14,545	14,694	14,557
Medium Strength	**CON**	**EXT**	**AO**	**A2OS**	**BD5S**	**A2O**	**BD5**
MS_X_00_000	19,026	10,313	20,002	18,767	17,990	14,443	13,477
MS_X_00_001	18,645	10,037	19,668	18,614	17,574	14,285	12,948
MS_X_00_AED	11,045	8,737	12,677	12,097	11,835	10,596	10,540
MS_X_00_AND	9,423	8,869	11,443	8,489	8,186	8,362	8,483
MS_X_TH_AND	9,255	8,128	9,691	7,627	7,554	7,570	7,610
Low Strength	**CON**	**EXT**	**AO**	**A2OS**	**BD5S**	**A2O**	**BD5**
LS_X_00_000	10,614	5,338	11,212	10,573	10,038	7,833	7,339
LS_X_00_001	10,375	5,160	10,999	10,339	9,800	7,527	7,056
LS_X_00_AED	5,685	4,401	6,682	6,592	6,245	5,566	5,452
LS_X_00_AND	4,853	4,473	5,832	4,687	4,288	4,747	4,369
LS_X_TH_AND	3,567	4,067	4,601	4,102	3,830	4,173	3,938

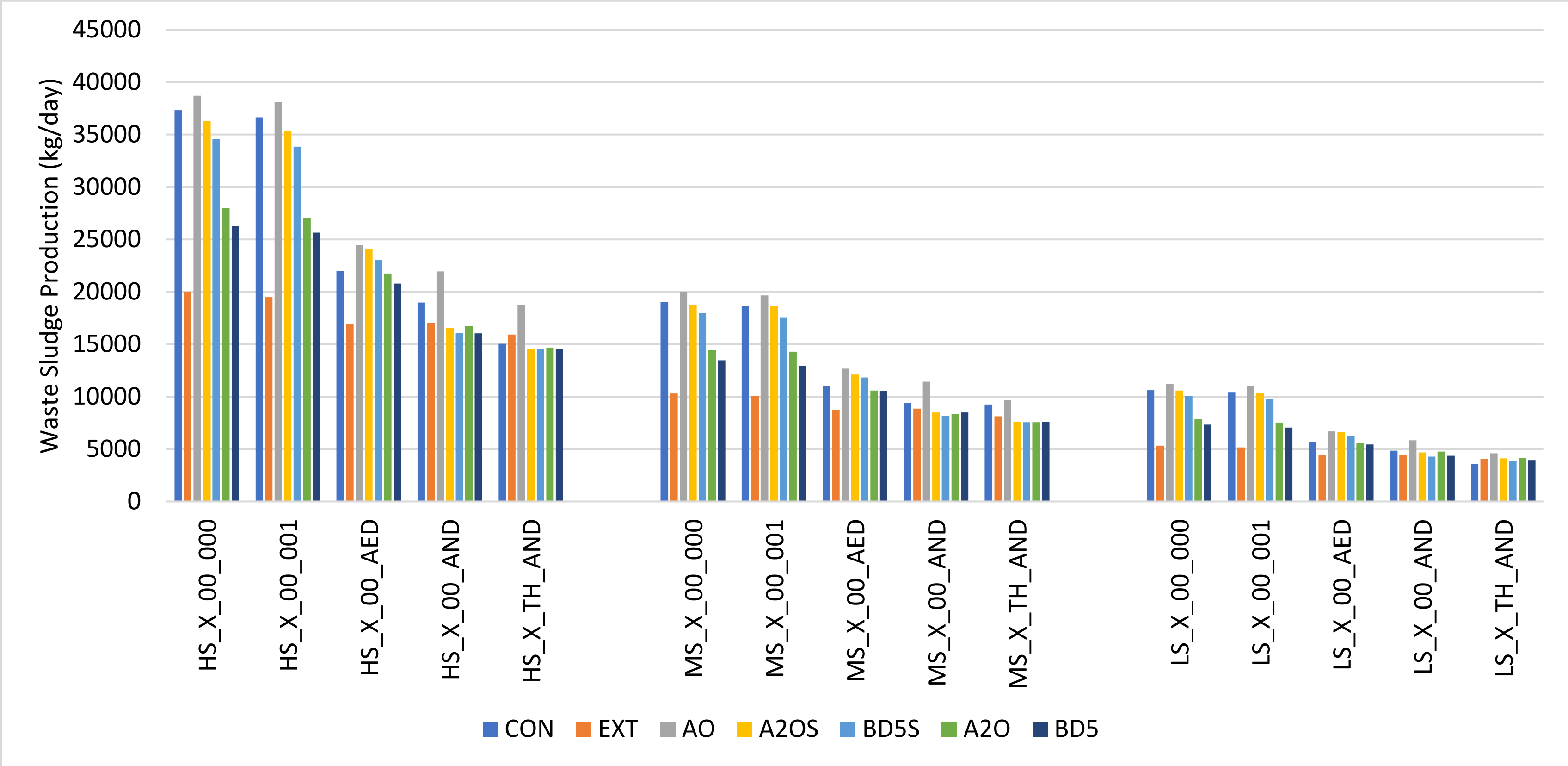

Figure 3-5 Waste Sludge Production of The Models

For all wastewater strengths and sludge processing options, waste sludge solid production ranged between 3,567 kg/day and 37,328 kg/day for conventional AS, 4,067 kg/day and 19,995 kg/day for extended aeration, 4,601 kg/day and 38,709 kg/day for A/O, 4,102 kg/day and 36,305 kg/day for A2O with primary settling, 4,173 kg/day and 27,999 kg/day for A2O with no primary settling, 3,830 kg/day and 34,575 kg/day for Bardenpho5 with primary settling, and finally 3,938 kg/day and 26,265 kg/day for Bardenpho5 with no primary settling (Table 3-7). For all ranges given for a specific treatment process, combinations that included anaerobic digestion with thermal hydrolysis have the lowest daily waste sludge production. On the other hand, among the wastewater treatment options extended aeration combinations have the lowest daily waste sludge production.

The highest waste sludge values were observed for cases where no action is taken for sludge processing. Compared to the "No Action" option in sludge processing (S_X_00_000 cases), thickening and dewatering (S_X_00_001) decreased waste sludge solids content by 3% on average for all treatment options. However, the volumetric reduction of the thickening and dewatering is necessary for a default WWTP.

Compared to the "No Action" option in sludge processing (S_X_00_000 cases), aerobic sludge processing (S_X_00_AED cases) decreased waste sludge solids by up to 46% for conventional activated sludge process, 18% for extended aeration, 40% for A/O, 38% for A2O with primary sedimentation, 29% for A2O with no primary sedimentation, 38% for Bardenpho5 with primary sedimentation, and 26% for Bardenpho5 with no primary sedimentation depending on the strength of the wastewater.

Compared to the "No Action" option in sludge processing (S_X_00_000 cases), Anaerobic sludge processing (S_X_00_AND cases) decreased waste sludge solids by up to 54% for conventional activated sludge process, 16% for extended aeration, 48% for A/O, 56% for A2O with primary sedimentation, 42% for A2O with no primary sedimentation, 57% for Bardenpho5 with primary sedimentation, and 40% for Bardenpho5 with no primary sedimentation depending on the strength of the wastewater.

Lastly, compared to the "No Action" option in sludge processing (S_X_00_000 cases), Anaerobic sludge processing with thermal hydrolysis (S_X_TH_AND cases) decreased waste sludge solids by up to 66% for conventional activated sludge process, 24% for extended aeration, 59% for A/O, 61% for A2O with primary sedimentation, 48% for A2O with no primary sedimentation, 62% for Bardenpho5 with primary sedimentation, and 46% for Bardenpho5 with no primary sedimentation depending on the strength of the wastewater.

The low SRT treatment technologies such as conventional AS and A/O processes have maximum sludge output among the models (S_CON_Y_Z and S_A/O_Y_Z cases). Although it appears to be a disadvantage, anaerobic digestion performance in these systems is much higher than in other systems. Due to the amount of secondary sludge with the addition of primary sludge of the systems, in these models, it was observed that biogas production rates of anaerobic digestion increased by up to 827 m^3/h for HS wastewater. The extended aeration had 85% lower biogas production rates while A2O and Bardenpho-5 processes had 70 and 80 % lower production rates respectively. Lastly, A2OS and Bardenpho-5S (with primary sedimentation) processes had 20 and 21 % lower biogas production rates in anaerobic digestion with respect to A/O process.

In the absence of primary sedimentation for wastewater treatment options such as extended aeration, and A2O and Bardenpho-5 without sedimentation, it was observed that the VSS destruction performance of the sludge stabilization is decreasing. For A2O process without primary sedimentation, the performances of aerobic, anaerobic and anaerobic with thermal hydrolysis sludge processes are decreased by 27%, 26% and 21%, respectively concerning the A2O process with primary sedimentation. For Bardenpho-5 process without primary sedimentation, the performances of aerobic, anaerobic and anaerobic with thermal hydrolysis sludge processes are decreased by 35, 29 and 24 % compared to with primary sedimentation counterpart.

In the cases, where anaerobic digestion was used, the effluent phosphorous results are usually higher as expected (Table C-3 to Table C-7) (Carrère et al., 2010). Therefore, for the wastewater treatment options, targeting TP removal (A/O, A2O and Bardenpho-5), P removal by salt is needed for further nutrient removal in addition to biological means. However, the addition of metal salts such as aluminum salts was found to be not enough to remove P for high strength wastewaters in meeting desired effluent TP concentrations. In addition to that, TN target effluent could not be reached with Bardenpho-5 or A2O treatment units with biological sludge stabilization processes. Yet, it was realized via modeling also that struvite precipitation after anaerobic digestion is solving the problem for both TN and TP effluent. It can be stated that struvite precipitation is an excellent tool for capturing P and N nutrients after anaerobic digestion. The cases, where precipitation methods were used are listed in Table 3-8. The aluminum salt solution was used for chemical precipitation in paced amount for TP influent which corresponds to 5.2 m^3/day, 3 m^3/day and 1.3 m^3/day for HS, MS and LS wastewaters, respectively. For struvite recovery, cyclone separator with Mg addition was used. It was observed that 900, 540 and 240 kg/day struvite recovery is possible for HS, MS and LS wastewaters respectively.

Table 3-8 The Cases in Which Precipitation Methods were Used

Sludge Treatment	Precipitation Used in Models				
	Treatment Process (X)				
High Strength	**AO**	**A2OS**	**BD5S**	**A2O**	**BD5**
HS_X_00_AED	-	PP	PP	PP	PP
HS_X_00_AND	PP	PP,SP	PP,SP	PP,SP	PP,SP
HS_X_TH_AND	PP	PP,SP	PP,SP	PP,SP	PP,SP
Medium Strength	**AO**	**A2OS**	**BD5S**	**A2O**	**BD5**
MS_X_00_AED	-	PP	PP	PP	PP
MS_X_00_AND	PP	PP,SP	PP,SP	PP,SP	PP,SP
MS_X_TH_AND	PP	PP,SP	PP,SP	PP,SP	PP,SP
Low Strength	**AO**	**A2OS**	**BD5S**	**A2O**	**BD5**
LS_X_00_AED	-	PP	PP	PP	PP
LS_X_00_AND	PP	SP	SP	SP	SP
LS_X_TH_AND	PP	SP	SP	SP	SP

PP = Phosphorous Precipitation
SP = Struvite Precipitation

Although the targeted TN and TP effluent concentration could not be reached when there is a biological sludge stabilization unit, there are WWTPs already having BNR technologies (A2O or Bardenpho-5) with anaerobic digestion combinations in Turkey. Examples are Antalya Hurma Urban Wastewater Treatment Plant (ASAT, 2005) İstanbul Tuzla Municipal Wastewater Treatment Plant (İSKİ, 2009), İstanbul Ambarlı Wastewater Treatment Plant (İSKİ, 2012), Konya Municipal Wastewater Treatment Plant (KOSKİ, 2009). In these WWTPs, chemicals might be needed to apply to remove the additional P released via precipitation.

In the modeling phase of the study, the sizing of wastewater treatment options was done to achieve around 93, 90 and 87 % COD removal efficiency for all high, medium and low strength wastewaters. In other words, it was aimed to keep effluent COD concentration between 40-60 mg/l. It was observed that TP and TN removal efficiencies were not affected by more than 3% by different sludge treatment options if required phosphorous and struvite precipitation were applied. It was also observed that if a biological sludge stabilization process added to an existing BNR system, effluent targeted TP and TN could not be achieved. Therefore, the biological sludge stabilization processes should be modeled in the design stage of a WWTP and the sizing of the bioreactors can be optimized to reach minimum chemical usage. Average removal efficiencies of conventional AS, Extended aeration and A/O processes are provided in Table 3-9. Average removal efficiencies of A2O and Bardenpho-5 processes are provided in Table 3-10.

Table 3-9 Removal Efficiencies of Conventional AS, Extended Aeration and A/O Processes

Model Name	Average Removal Efficiency (%)			
	BOD	TSS	TN	TP
HS_CON	98.0	97.6	27.2	47.7
MS_CON	95.9	94.7	24.4	42.7
LS_CON	93.6	92.0	25.5	40.2
HS_EXT	99.1	97.6	22.8	31.5
MS_EXT	98.7	96.8	20.4	36.7
LS_EXT	97.6	94.3	22.1	25.8
HS_AO	97.7	96.4	42.1	93.0
MS_AO	96.5	94.7	39.9	88.7
LS_AO	93.7	91.2	26.3	78.5

Table 3-10 Removal Efficiencies of A2O and Bardenpho-5 Processes

Model Name	Average Removal Efficiency (%)			
	BOD	TSS	TN	TP
HS_A2OS	98.3	97.0	78.2	89.4
MS_A2OS	97.4	95.5	64.1	84.8
LS_A2OS	95.9	94.2	58.1	82.1
HS_BD5S	97.9	95.6	86.8	91.1
MS_BD5S	97.2	94.2	80.5	86.6
LS_BD5S	95.6	92.3	73.3	76.9
HS_A2O	97.7	95.2	80.3	86.4
MS_A2O	96.4	92.6	70.3	80.3
LS_A2O	94.8	90.1	63.2	77.7
HS_BD5	98.1	95.2	87.8	92.8
MS_BD5	96.4	91.4	85.3	85.7
LS_BD5	94.8	89.6	76.2	74.2

It was observed that Bardenpho-5 process is superior to the A2O process in the removal of nitrogen and phosphorous. It was also observed that struvite recovery is improving nitrogen removal efficiency under 1% for these nutrient removal systems. In the selected influent characteristics, TKN/COD ratio is 0.085. The typical range of TKN/COD ratio can drop down to 0.07 (Rössle et al., 2001). It was observed that high strength wastewater and A2O models could achieve higher nitrogen removal efficiencies with 1000 mg/l COD influent. This is due to the fact that at higher influent COD concentration of 1000 mg/l (higher than the selected maximum level of 800 mg/L), a lower TKN/COD ratio of 0.07 is obtained. This low ratio or high influent COD level supplies carbon source for denitrification and results in lower effluent TN concentrations. If the influent COD is increased to have a TKN/COD ratio of 0.07, nitrogen removal of A2O process increases by 2.5% while 1% for Bardenpho-5 process.

3.4. Conclusions

In this study, Turkey’s mostly used wastewater and sludge treatment technologies were investigated. Selected treatment options were used to create scheme combinations to be modeled in BioWin simulation environment. In models, flowrate was determined as 100,000 m^3/day. In the creation of the models, sizing of the bioreactors and operation variables were kept in the range of typical design parameters to meet target effluent criteria. Moreover, for better comparison, operational variables were kept constant for different sludge treatment options. In this study, 105 treatment scheme combinations were created.

Among the wastewater treatment options, it was observed that extended aeration wastewater treatment option has the lowest daily sludge production. Yet, the system has the biggest land footprint compared to the others. Among the sludge treatment options, anaerobic digestion with thermal hydrolysis was found to have the smallest amount of daily waste sludge production. On the other hand, it was observed that conventional AS and A/O processes have the biggest biogas production rate in anaerobic sludge processes, for producing the highest amount of sludge.

It was observed that A2O and Bardenpho-5 processes could work with or without primary sedimentation. However, for biological sludge process combinations of these treatment technologies, phosphorous or struvite precipitation is needed to meet nutrient effluents since the sizing of the bioreactors was done without any sludge treatment option. With primary sedimentation, sludge stabilization efficiencies as VSS destruction are increasing 20.5% on average. Without primary sedimentation, nutrient removal efficiencies are increasing 4.4% for A2O process and 2.8% for Bardenpho-5 process. It was also observed that the removal efficiency of TN is effected differently for A2O and Bardenpho-5 processes by influent TKN/COD ratio.

Due to variations in the waste sludge production, available sludge management options should be a significant deciding factor in selecting wastewater and sludge treatment options. However, while selecting the wastewater and sludge treatment options, waste sludge production and removal efficiency of the treatment system should not be the only factors to investigate. Energy consumption, GHG emissions and cost analysis should also be investigated for designing sustainable and economical WWTPs. In this context, these analyses are provided in the following chapter (Chapter 4).

CHAPTER 4

COMPARISON OF DIFFERENT TREATMENT SCHEMES BASED ON ENERGY CONSUMPTION AND CARBON FOOTPRINT FOR MUNICIPAL WWTPS

4.1. Introduction

WWTPs are among the primary substructures for populated areas in order to prevent waterborne diseases and minimize environmental pollution. The number and capacity of WWTPs are expected to increase in the following years due to population growth and industrialization (Qin et al., 2014). The amount of wastewater treated has reached to 3,842 million m^3 in Turkey in 2016 (TUIK, 2016b).

Wastewater treatment is an energy-intensive process. Growing energy consumption is considered as a global problem for humankind, especially considering GHG emissions as well as increasing operating costs (Ashrafi et al., 2014). Many countries are struggling to convert energy resources from fossil fuels to renewables and optimize energy consumption through strategic changes in design and operation. Today 25% of the energy consumption in the water sector is linked to wastewater collection and treatment (Li et al., 2019). This amount corresponds to 1% to 4% of the total energy consumption worldwide (IEA, 2016). Moreover, by 2040, the energy used for wastewater works will exceed 60% of the total energy used in the water sector if the demands are as projected (IEA, 2016).

WWTPs are one of the sources of GHG emissions not only due to energy consumption for operations but also processes and reactions occurring during treatment. GHGs emitted from domestic WWTPs are CO_2, CH_4, and N_2O (Delre et al., 2019). These gasses are the most significant contributors to climate change (IPCC, 2014). When energy consumption and GHG emissions due to treatment processes are considered, the global warming effect of a WWTP needs consideration. This problem drew attention to energy efficiency studies on this subject (Wu et al., 2010). However, there is no legislation or limitation regarding energy consumption in WWTPs. So, energy consumption varies significantly among different plants. Especially for municipal WWTPs, being only in community service and not having a profit goal makes wastewater management hard to regulate. Economic benefits of wastewater management are still an issue for local governments of developing and underdeveloped countries (Crisan et al., 2018). Some of the nationally averaged unit energy consumptions per 1 m^3 of wastewater treated are listed in Table 4-1.

Table 4-1 Average Unit Energy Consumptions in WWTPs in different countries (kWh/m^3 of wastewater treated) (Hernández-Sancho et al., 2011)

United States	**Netherlands**	**Singapore**	**Switzerland**
0.45	0.36	0.56	0.52
Germany	**United Kingdom**	**Australia**	**Spain**
0.67	0.64	0.39	0.53

In Portugal, 17 WWTPs were examined to obtain performance indicators. These plants each treat around 10,000 m^3/day of wastewater and most of them have biogas production (Silva et al., 2015). The study proposed a performance classification according to energy consumption. In that study, it was stated that, for AS configurations, if the energy consumption of the treatment plant is below 0.28 kWh/m^3, the energy performance of the plant is considered as in good state. On the other hand, it was also stated, for BNR processes, in order to define energy performance as in good state, the energy consumption of the facility needed to be less than 0.42 kWh/m^3 (Silva et al., 2015).

The aim of this study is to compare different wastewater treatment processes and schemes in terms of energy consumptions, carbon footprints and net present values (NPVs) for different wastewater strengths through modeling. BioWin software was used to model different treatment schemes as discussed in Chapter 3. WWTPs can be simulated in a computer environment for different scenarios (Henze et al., 2017). Therefore, instead of working on an actual treatment plant, models can easily be duplicated for different schemes. In this study, energy consumption and carbon footprints were assessed based on model outputs. Potential impacts of energy usage, carbon footprint, and NPV on treatment system selection were evaluated.

4.2. Methodology

In this study, most used municipal WWTP treatment schemes of Turkey, which were modeled in Chapter 3, were investigated in terms of energy consumption, carbon footprint and NPV. A total of 105 different treatment scheme models were investigated in this regard. BioWin 5.3 software was used for simulation. Energy consumption data of the modeled treatment plant were obtained from software while, carbon footprint and NPV of the treatment schemes were calculated externally.

The methodology consists of the following steps; i) modeling different treatment schemes ii) calculation of energy consumption iii) calculation of carbon footprint iv) cost analysis. The purpose of this procedure is to obtain and compare the energy consumption, carbon footprint and NPV of the generated treatment scheme models.

For this study, two levels of energy consumption were defined which is named specific energy consumption (SEC) 1&2. SEC1 represents the energy consumption (in kWh) per 1 m^3 of treated wastewater. SEC2 represents energy consumption per 1 mg/L of COD treated. On the other hand, carbon footprint results were defined for hourly GHG emissions ($kgCO_2eq/h$). Lastly, NPV of each system was calculated for 20 years operation period and defined in million TL.

4.2.1. Modeling different treatment schemes

Wastewater treatment schemes used for comparison were selected based on common treatment processes in Turkey as studied in a TUBITAK KAMAG project (T.C. Çevre ve Şehircilik Bakanlığı, 2015). According to the results presented in that project, among the 282 municipal WWTPs, 44% are biological nutrient removing systems (BNRs). This is followed by conventional activated sludge (CAS) treatment by 35%. Then comes extended aeration by 15%. Trickling filters and ponds have a share of 3% each. Among BNRs, most common treatment systems are A2O, Bardenpho5 and AO (Phoredox) with a share of 52%, 40% and 5%, respectively. Sludge stabilization is applied only at 25% of all municipal WWTPs. Common sludge stabilization methods are aerobic digestion and anaerobic digestion applied at 53% and 29% of the WWTPs, respectively.

Using the above information as a guide as well, treatment system simulations and comparisons were realized for CAS, extended aeration, AO, A2O, and Bardenpho-5. In extended aeration, primary sedimentation was not used as it is not common (Stensel et al., 2014). For A2O and Bardenpho-5 processes, both primary sedimentation usage and absence were modeled since both practices can be observed in the municipal WWTPs in Turkey (Gülhan et al., 2018).

These systems were considered under five different sludge management options. These are (1) no action, (2) thickening and dewatering, (3) thickening, aerobic digestion and dewatering, (3) thickening, anaerobic digestion and dewatering, and finally (5) thickening, pre-treatment, anaerobic digestion and dewatering. The first sludge management option was used as a base case where no action is applied to sludge. Therefore, the impact of different sludge handling methods and stabilization on energy usage and carbon footprint could be compared. The fifth option aims to pre-treating the wastewater to improve the efficiency of anaerobic digestion. Thermal hydrolysis was considered as the pre-treatment method since it is a proven technology to improve the performance of anaerobic digestion (Carrère et al., 2010).

A single flow rate was selected to compare all treatment processes on energy consumption and carbon footprint. In total, 61% of the municipal wastewater is handled at WWTPs with a capacity of 100,000 m^3/day or higher (TUBITAK KAMAG, 2015). This value was chosen as the influent flowrate for all WWTPs simulated. Three different strengths of wastewater were considered. Wastewater characteristics are provided in Table 4-2 (Stensel et al., 2014).

Table 4-2 Characteristics for Different Wastewater Strengths (Stensel et al., 2014)

Constituents	Concentrations (mg/L)		
	Low strength WW	Medium strength WW	High strength WW
BOD_5	110	190	350
COD	250	430	800
TSS	120	210	400
NH_3-N	12	25	45
Organic-N	8	15	25
TKN	20	40	70
Organic-P	1	2	4
Inorganic-P	3	5	8
Oil & grease	50	90	100

Naming convention was used to identification of the process combinations simulated. The form of the naming convention is S_X_Y_Z. S is representing the strength of the wastewater treated. X is representing the treatment process used. Y is representing the sludge pre-treatment process. And finally, Z is representing the sludge process option. Definitions are provided in Table 3-3 (Chapter 3, Heading 3.2.3).

In simulating different treatment schemes, it was assumed that all cases target effluent characteristics that are required for domestic WWTPs serving a population equivalent (PE) of 100,000 or more. Accordingly, the lowest possible PE was calculated as

183,333 capita. The calculation was made based on the BOD generation of Turkey which is 45-60 g/cap.day (T.C. Çevre ve Şehircilik Bakanlığı, 2004, 2014). Therefore, the effluent limits taken from the regulations are as stated in Table 3-4.

Bioreactor sizing for different treatment schemes was done using typical design parameters (Table 2-1, Table 2-2) to meet the discharge limits (Table 3-4). In order to make a viable comparison between energy consumption and carbon footprint, most of the variables were set as the default values of BioWin. Other assumptions or non-default values are such that;

- Primary sedimentation underflow solid concentration is typically between 4 and 5.5% (Sanin et al., 2011; Stensel et al., 2014) Therefore, underflow rates are adjusted to operate at 45,000 mg/L TSS concentration.
- The surface over flowrate of secondary clarifiers was adjusted to operate between 16 to 32 m^3/m^2.day (Stensel et al., 2014).
- In conventional activated sludge and extended aeration systems, surface aerators are used. In BNR systems aeration is supplied through diffusers.
- There are four pumps placed in the models. The names and head pressures of the pumps are inlet, RAS, WAS, IR pump and 8, 8, 4 and 0.25m respectively.
- Thickening and dewatering capture rates are set as 90% according to Sanin et al. (2011). The default is 100%.
- Thickening underflow TSS concentration is fixed around 70,000 mg/L. On the other hand, for cases in which aerobic digestion is used, the value is fixed in the range 40,000-50,000 mg/L (Sanin et al., 2011).
- Waste sludge TSS concentration is kept above 22% (Sanin et al., 2011).
- In order to meet discharge standards, chemical addition is applied if necessary. Added chemicals are aluminum salt in secondary clarifiers to meet TP target in the discharge and calcium carbonate for pH control in aerobic digestion. In addition to that, struvite recovery was applied to AD sludge processes if necessary.

- Methane produced in anaerobic digestion is assumed to be used in the system through a combined heat and power (CHP) unit.

Design parameters of models used in simulations of different cases are provided in Appendix A, Table *A-1* to Table *A-7*. Moreover, process flow schemes used for different treatment methods and sludge handling flowsheet representation are provided in Appendix B, Figure B-1 to Figure B-9.

4.2.2. Energy Consumption Calculation

The BioWin software enables power consumption analyses of an identified model if relevant inputs are provided. In "*Power Table*" from BioWin album window, energy consumption per hour can be accessed for blowers, mixing, pumping and solid/liquid separation. Results are provided in kWh. In expressing energy consumptions, two different specific energy consumption (SEC) units were considered. These are SEC1 and SEC2. The first one represents energy consumption (in kWh) per 1 m^3 of treated wastewater. The second one represents energy consumption per 1 mg/L of COD treated.

4.2.3. Carbon Footprint Calculation

In determining the carbon footprint of a treatment case, indirect and direct GHG emissions were calculated then summed to achieve the total carbon footprint of the system. Firstly, direct emissions were calculated. In "*Rates Table*" from BioWin album window, CO_2 CH_4 and N_2O stripping of each bioreactor can be selected to display as process rates. All direct gas emissions were needed to be converted to CO_2 equivalence. CH_4 and N_2O gasses have respectively 25 and 298 equivalence of CO_2 (US EPA, 2016). Methane production from anaerobic digestion was assumed to be converted CO_2. Secondly, indirect emissions were taken into consideration by calculating GHG emissions arising from energy consumption and sludge transportation of the modeled facilities. Weighted carbon emissions per 1 kWh electricity production of Turkey can be calculated as 540 gCO_2eq/kWh (POSTNOTE, 2006). On the other hand, carbon emissions during sludge transportation per tonne-km were taken as 140g/ton.km (EEA, 2017). For all cases waste sludge was assumed to be transported for 10 km.

4.2.4. Cost Calculations

In “*Cost Table*” from the BioWin album window, power, chemical, fuel cost and cost spend on sludge are represented. In order to achieve the cost results of the created models, relevant unit costs were needed to be determined. Before, determining the unit costs, the money unit used in models was selected as TL. In Turkey, 1 kWh of energy has a cost of approximately 0.4 TL according to Energy Market Regulatory Authority (EPDK, 2018). On the other hand, care was given to use market costs for chemicals and fuel. Aluminum dust price was found as 1 TL per liter (Balmumcu Kimya LTD. ŞTİ., 2019). The natural gas unit price was taken from EPDK, as approximately 1 TL/m^3 (EPDK, 2019) which is used as fuel for heating of the anaerobic digestor. Lastly, for sludge handling costs, two-unit costs were entered. These could be described as sludge transportation costs and tipping fee costs for solid waste landfilling. Although sludge landfilling is not a sustainable sludge management method, in this study, it was used for comparison of different treatment cases on the same basis. Transportation unit cost varies between 12-25 TL/ton.km in market (Süreko, 2019). The transportation cost was assumed as 22.5 TL/ton.km. For all cases, sludge was assumed to be transported for 10 km. Sludge tipping fee at the landfill site was taken from the İstanbul Metropolitan Municipality as 159 TL/ton (İBB, 2019).

With the inputs provided, BioWin software represents management costs in TL/h. Capital cost and net present value for a management period of 20 years were calculated externally.

In calculating the initial cost of a system, three categories were considered. The first one is the construction of the reactor's initial cost. The second one is the machinery & equipment initial cost, and finally, the last one is the capital cost of piping. The piping cost was added as 10% of construction cost (T.C. Çevre ve Şehircilik Bakanlığı, 2019).

Reactor's initial cost

In predicting the construction or reactor's initial cost, it was assumed that 0.6 m wall thickness is used in constructing a structure. Moreover, the unit of cost of reinforced concrete was taken as 190 TL/m^3 (T.C. Çevre ve Şehircilik Bakanlığı, 2019). It was assumed that 100 kg steel is used for reinforcement of 1 m^3 of concrete. The unit cost of steel was taken as 3500 TL/tons (T.C. Çevre ve Şehircilik Bakanlığı, 2019). The depth of the bioreactors was assumed 5 m. The length/width ratio of the units was assumed to be 4 (Stensel et al., 2014). The total volume of the reactors was assumed to be same with design parameters of created models used in simulations which are provided in Appendix A between *Table A-1* and *Table A-7*. A simple volumetric calculation was applied for building construction costs (Equation 3-6).

$$C_0 = V_c * (C_c + M_r * C_r) \tag{3}$$

$$V_c = V_e - V_i \tag{4}$$

$$V_i = l * d * w \tag{5}$$

$$V_e = (l + 2 * t_w) * (d + t_w) * (w + 2 * t_w) \tag{6}$$

Where,

C_0 = Reactor's Initial Cost (TL)

V_c = Volume of concrete (m^3)

C_c = Unit cost of concrete (tl/m^3)

M_r = Steel used for reinforcement (kg/m^3)

C_r = Unit cost of steel (tl/kg)

V_e = External volume of the reactor (m^3)

V_i = Internal volume of the reactor (m^3)

l = length of the reactor (m)

d = depth of the reactor (m)

w = width of the reactor (m)

The initial cost of grit chamber and primary sedimentation were also calculated using a similar method. Moreover, the number of grit chambers was assumed to be four and the number of primary sedimentation tanks was assumed to be two for 100,000 m^3/day flowrate. The slope of the primary sedimentation was neglected in calculation of the initial cost.

The number of secondary clarifiers was assumed to be six for the selected flow rate. Secondary clarifiers were assumed to have two different parts which are 4.5 m depth cylindric and 1 m depth conic shapes. The radius was assumed to be 8 m. A simple volumetric calculation was applied for the construction costs of secondary clarifiers (Equation 7-10).

$$C_{0c} = V_{cc} * (C_c + M_r * C_r) \tag{7}$$

$$V_{cc} = V_{ec} - V_{ic} \tag{8}$$

$$V_{ic} = r^2 * \pi * d_{cly} + r^2 * \pi * d_{con}/3 \tag{9}$$

$$V_{ec} = (r + t_w)^2 * \pi * d_{cly} + (r + t_w)^2 * \pi * d_{con}/3 \tag{10}$$

Where,

C_{0c} = Clarifier's initial cost (TL)

V_{cc} = Volume of concrete (m^3)

C_c = Unit cost of concrete (tl/m^3)

M_r = Steel used for reinforcement (kg/m^3)

C_r = Unit cost of steel (tl/kg)

V_{ec} = External volume of the clarifier (m^3)

V_{ic} = Internal volume of the clarifier (m^3)

r = Radious of the clarifier (m)

d_{cly} = Depth of the cylinder (m)

d_{con} = Depth of the cone (m)

Initial costs for anaerobic digestion, thermal hydrolysis and CHP units could not be found in the Turkish market. Therefore, international resources were used. Anaerobic digestion unit capital cost was taken as 600 \$/m^3 (Scion, 2013). CHP unit capital cost was taken as 2,500 \$/kW (Abu-Orf et al., 2014). The thermal hydrolysis capital cost can be found between 2.5 million and 35 million \$ on the market (Abu-Orf et al., 2014; UBC, 2017; WBDG, 2016). The thermal hydrolysis processes used in models (Figure B-9) are similar to Lysis-Digestion systems where the TH price was found as 40% of the digestion capital cost (Abu-Orf et al., 2014). Therefore, thermal hydrolysis capital cost was assumed to be 40% of the anaerobic digestion cost.

<u>The machinery & equipment initial cost</u>

Machinery & equipment prices were gathered from the market through personal contacts. Prices are listed in Table 4-3. In converting the USD currency to TL, a currency conversion factor of 5.47 is used (21 March 2019).

Table 4-3 Machinery & Equipment Capital Costs

Machinery & Equipment	Unit Cost (USD)	Unit Cost (TL)	References
Scada system	12,400	67,828	Prizma Automation
Grit scraper	9,800	53,606	Arges
Primary scraper	13,500	73,845	
Secondary scrapper	15,200	83,144	
Diffusers	25	136	Sulzer
Mixer	1,500	8,205	Makro
Centrifugal dewatering	-	80,000	Haus
Belt filter (thickening)	-	30,000	Haus

Dewatering unit and thickening units with the known prices have a sludge process capacity of 50 m^3/h and 100m^3/h respectively. Furthermore, the number of dewatering and thickening unit was selected by WAS flowrate for each model. On the other hand, the number of diffusers was selected from BioWin unit details. Turbo blower and pump prices were also found in the market from Anadolu Flygt. The capacity price table is listed in Table 4-4.

Table 4-4 The Capacity and Price Table of Pumps and Turbo Blower

Equipment	Capacities (m^3/h)	Cost (TL)
Turbo Blowers	780	36,200
	4,500	497,500
	13,200	1,650,000
	22,000	2,139,000
WAS Pump	25	18,500
Inlet Pump	220	84,300
IR Pump	125	67,800
RAS Pump	75	59,700

The number of blowers and pumps was selected according to the airflow rate requirements of each treatment scheme modeled which is provided by BioWin output. On the other hand, one of each spare pumps and blowers were also considered in cost calculations.

For net present value calculations interest rate was taken as the inflation rate of Turkey between 2004 and 2018 after the economic stabilization (TUİK, 2019). Therefore, the interest rate was assumed at 9.4%. Turkey's yearly inflation rates are provided in Figure 4-1.

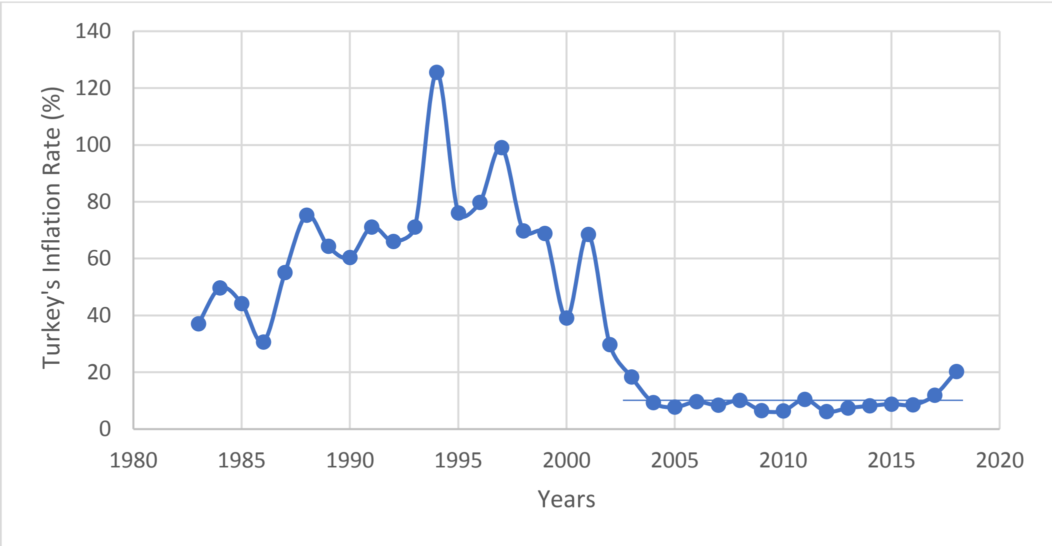

Figure 4-1 Turkey's Inflation Rate For Years (TUİK, 2019)

The operation period was assumed to be twenty years. On the other hand, yearly operation cost was considered to be affected by selected interest value every year since the interest rate was assumed as the inflation rate of Turkish Liras. An example of a cash flow diagram for WWTP is provided in Figure 4-2.

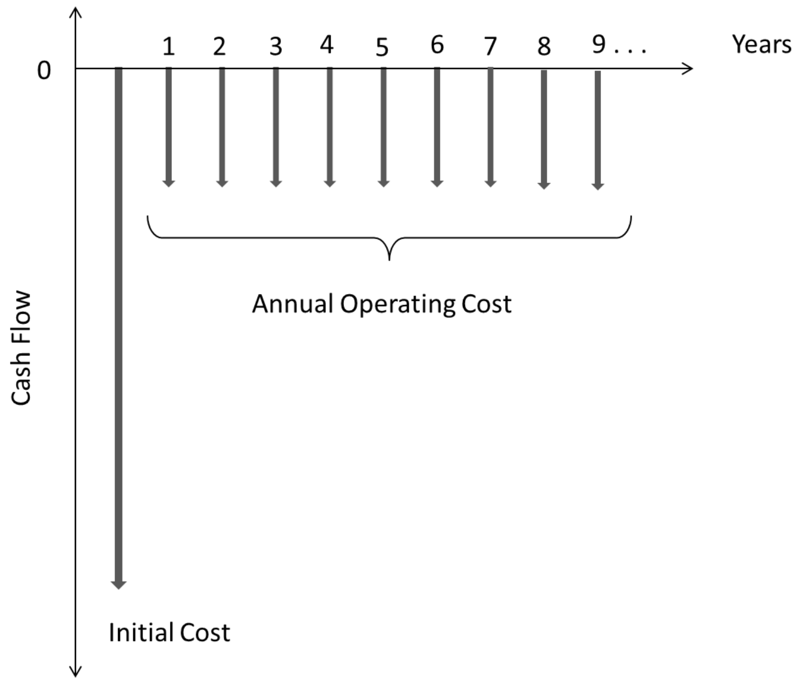

Figure 4-2 Cash Flow Diagram Example of a WWTP

4.3. Results and Discussion

In this part of the study, 105 different treatment cases that were created and modeled using BioWin were compared. Design parameters and resulting reactor volumes to reach target effluent concentrations are provided in Appendix C between Table *C-1* and Table *C-7*. Modeled cases were analyzed and compared in terms of energy consumption and carbon footprint. Additionally, the cost of the systems was also evaluated. Detailed results tables are provided in Appendix D between Table *D-1* and Table *D-7*. Detailed result tables include;

- Operation cost (TL/h)
- SEC1 (kWh/m3)
- SEC2 (kWh/ (mg/l) COD_r)
- Operation cost for wastewater processed (TL/m^3)
- Capital cost (M TL)

- 20-years NPV (M TL)
- 20-years NPV without capital cost (M TL)
- NPV per wastewater processed (M TL/m^3)
- Total GHG emissions (kgCO_2eq/h)

The model results were discussed in the following headings; i) specific energy usage, ii) carbon footprint and iii) 20-Years NPV.

4.3.1. Specific Energy Usage

To understand specific energy usage, two indicators were selected for discussion. These indicators are SEC1 (kwh/m^3) and SEC2 (kWh/ (mg/l) COD_r). Specific energy consumptions of the created models in terms of both SEC1 and SEC2 are provided in Table 4-5 and Table 4-6, respectively. A comparison of SEC1 and SEC2 for different cases is also provided in Figure 4-3 and Figure 4-4, respectively.

Table 4-5 SEC1 Results

	SEC 1 (kWh/m^3)						
	X (treatment method) in case definition						
Case	**CON**	**EXT**	**AO**	**A2O**	**A2OS**	**BD5**	**BD5S**
HS_X_00_000	0.48	0.77	0.25	0.46	0.36	0.49	0.36
HS_X_00_001	0.58	0.86	0.34	0.57	0.49	0.58	0.46
HS_X_00_AED	0.77	0.89	0.52	0.65	0.64	0.64	0.62
HS_X_00_AND	0.29	0.82	0.05	0.49	0.23	0.51	0.21
HS_X_TH_AND	0.25	0.81	0.05	0.29	0.18	0.36	0.17
MS_X_00_000	0.28	0.45	0.16	0.26	0.21	0.29	0.24
MS_X_00_001	0.33	0.51	0.21	0.31	0.27	0.34	0.31
MS_X_00_AED	0.43	0.52	0.31	0.35	0.35	0.38	0.38
MS_X_00_AND	0.18	0.49	0.05	0.26	0.12	0.33	0.17
MS_X_TH_AND	0.16	0.49	0.04	0.24	0.10	0.29	0.15
LS_X_00_000	0.16	0.27	0.09	0.17	0.15	0.20	0.17
LS_X_00_001	0.19	0.30	0.12	0.20	0.18	0.24	0.21
LS_X_00_AED	0.25	0.31	0.17	0.23	0.23	0.26	0.26
LS_X_00_AND	0.10	0.29	0.02	0.17	0.09	0.21	0.12
LS_X_TH_AND	0.10	0.29	0.00	0.15	0.07	0.22	0.11

Table 4-6 SEC2 Results

Case	SEC 2 (kWh/(mg/L COD_r)) X (treatment method) in case definition						
	CON	**EXT**	**AO**	**A2O**	**A2OS**	**BD5**	**BD5S**
HS_X_00_000	0.63	1.02	0.33	0.61	0.47	0.65	0.48
HS_ X_00_001	0.77	1.13	0.45	0.76	0.64	0.77	0.61
HS_ X_00_AED	1.01	1.17	0.70	0.87	0.84	0.85	0.82
HS_ X_00_AND	0.38	1.08	0.06	0.65	0.31	0.68	0.27
HS_ X_TH_AND	0.33	1.06	0.07	0.39	0.25	0.49	0.23
MS_ X_00_000	0.72	1.14	0.40	0.68	0.55	0.76	0.63
MS_ X_00_001	0.84	1.28	0.54	0.80	0.68	0.91	0.79
MS_ X_00_AED	1.09	1.32	0.79	0.92	0.90	0.99	0.99
MS_ X_00_AND	0.47	1.25	0.12	0.67	0.31	0.88	0.43
MS_ X_TH_AND	0.42	1.23	0.11	0.63	0.27	0.76	0.40
LS_ X_00_000	0.74	1.19	0.40	0.79	0.65	0.92	0.77
LS_ X_00_001	0.87	1.32	0.54	0.92	0.80	1.08	0.95
LS_ X_00_AED	1.14	1.36	0.79	1.04	1.02	1.18	1.17
LS_ X_00_AND	0.46	1.28	0.07	0.77	0.39	0.97	0.56
LS_ X_TH_AND	0.45	1.26	0.01	0.69	0.32	1.04	0.52

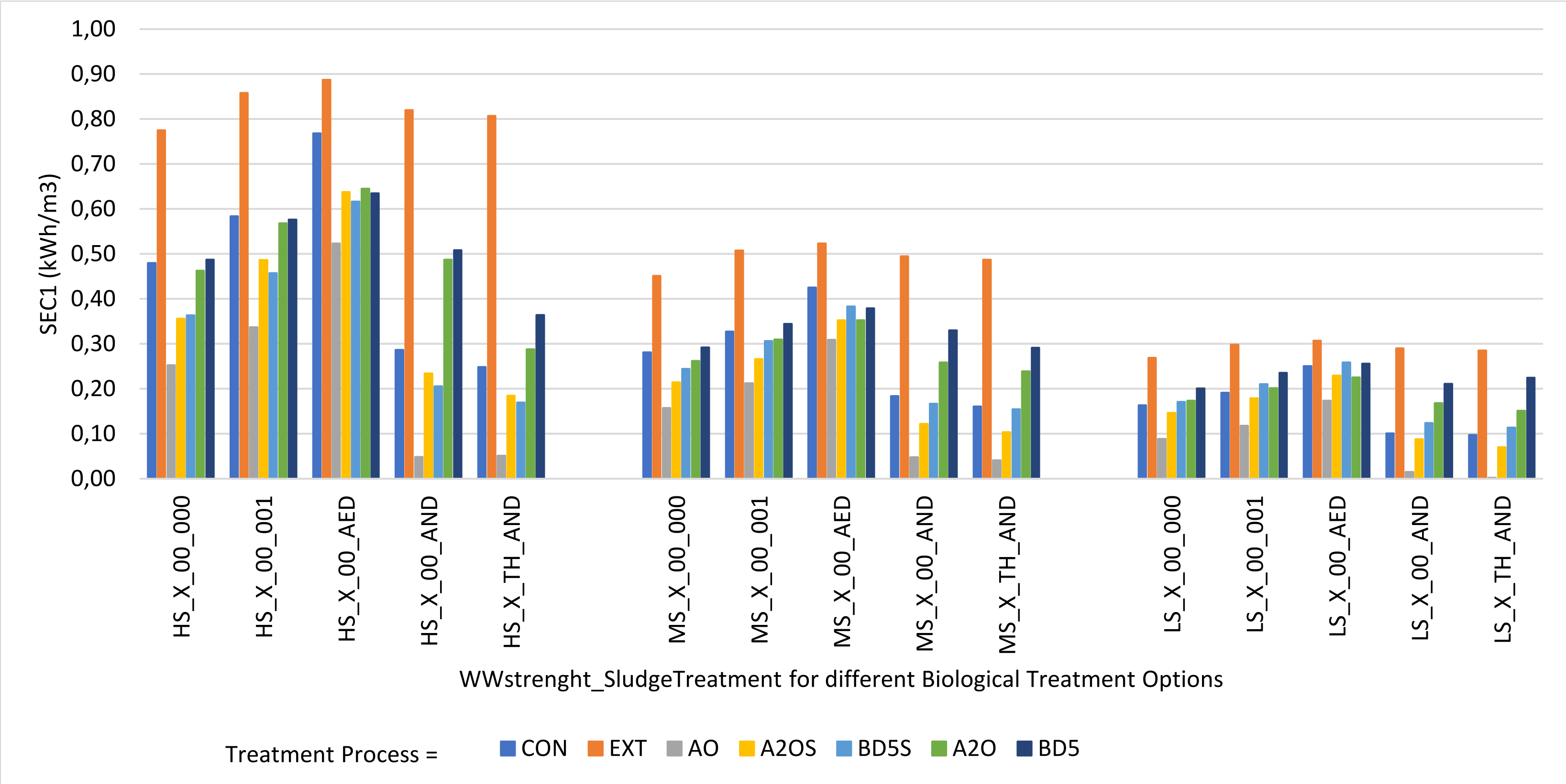

Figure 4-3 SEC1 Results

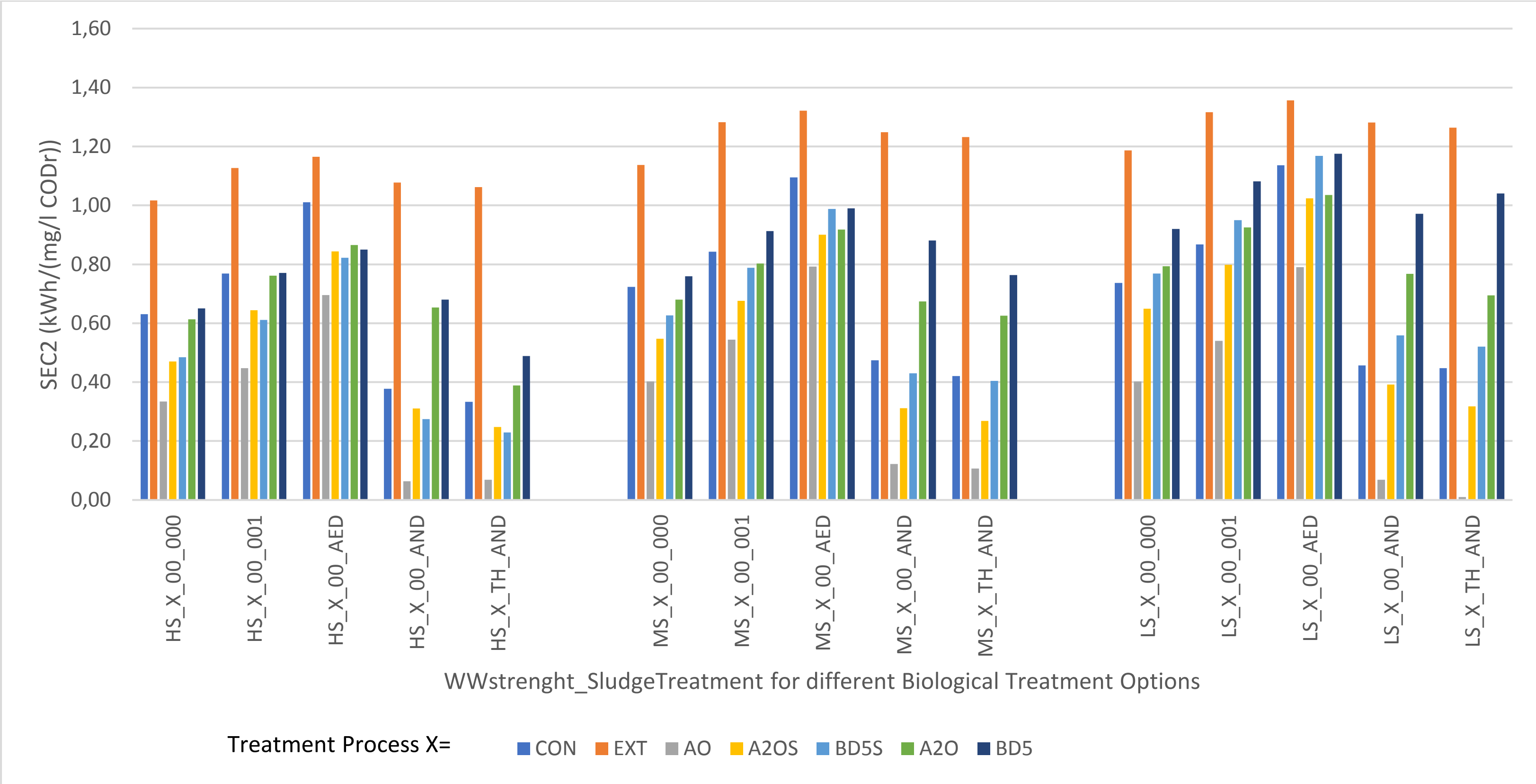

Figure 4-4 SEC2 Results

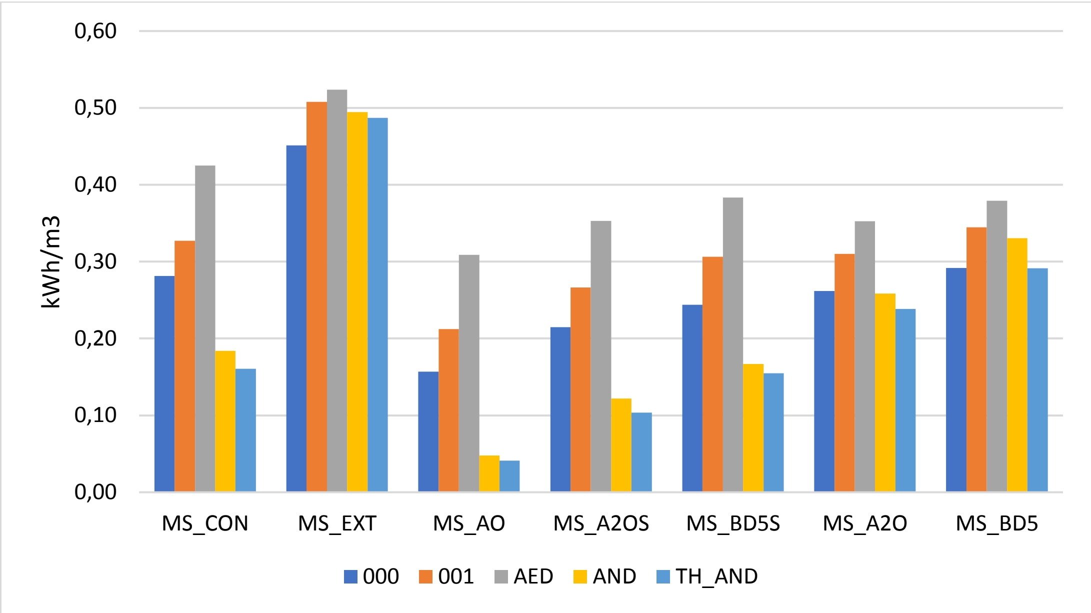

Figure 4-5 SEC1 Results for MS Wastewaters

For all wastewater strengths and sludge processing options, SEC1 ranged between 0.10 kWh/m^3 and 0.77 kWh/m^3 for conventional activated sludge, 0.27 kWh/m^3 and 0.89 kWh/m^3 for extended aeration, 0.002 kWh/m^3 and 0.52 kWh/m^3 for A/O, 0.07 kWh/m^3 and 0.64 kWh/m^3 for A2O with primary settling, 0.15 kWh/m^3 and 0.65 kWh/m^3 for A2O with no primary settling, 0.11 kWh/m^3 and 0.62 kWh/m^3 for Bardenpho5 with primary settling, and finally 0.20 kWh/m^3 and 0.64 kWh/m^3 for Bardenpho5 with no primary settling (Table 4-5). In literature, it was observed that SEC1 of a WWTP varies between 0.01 to 2.5 kWh/m^3 (Silva et al., 2015). It is also known that bigger capacity treatment plants are consuming less energy for 1 m^3 wastewater processed (Pabi et al., 2013). Therefore, the SEC1 results for hypothetical models with 100,000 m^3/day capacity seem reasonable since the selected capacity is at a high level. For all ranges given for a specific treatment process, combinations that included aerobic sludge stabilization have the highest SEC1 values. As expected, as the strength of the wastewater decreases, SEC1 value decreases for a specific treatment combination. SEC1 results for different sludge stabilization methods for MS wastewaters are provided in Figure 4-5.

The lowest SEC1 values are for cases where AD with thermal hydrolysis is taken for sludge processing. Compared to the "No Action" option in sludge processing (S_X_00_000 cases), thickening and dewatering increased SEC1 by up to 22% for conventional activated sludge process, 13% for extended aeration, 35% for A/O, 37% for A2O with primary sedimentation, 23% for A2O with no primary sedimentation, 26% for Bardenpho5 with primary sedimentation, and 18% for Bardenpho5 with no primary sedimentation depending on the strength of the wastewater. Since the models were built to achieve the same COD removal efficiencies, similar trends were observed for SEC2 as well (Figure 4-5 & Figure 4-6). The addition of primary sedimentation to A2O and Bardenpho5 decreases specific energy usage defined by SEC1. The increase in specific energy usage due to thickening and dewatering is less for extended aeration. This is due to lower sludge production amounts compared to other treatment processes. SEC2 results for different sludge stabilization methods for HS wastewaters are provided in Figure 4-6.

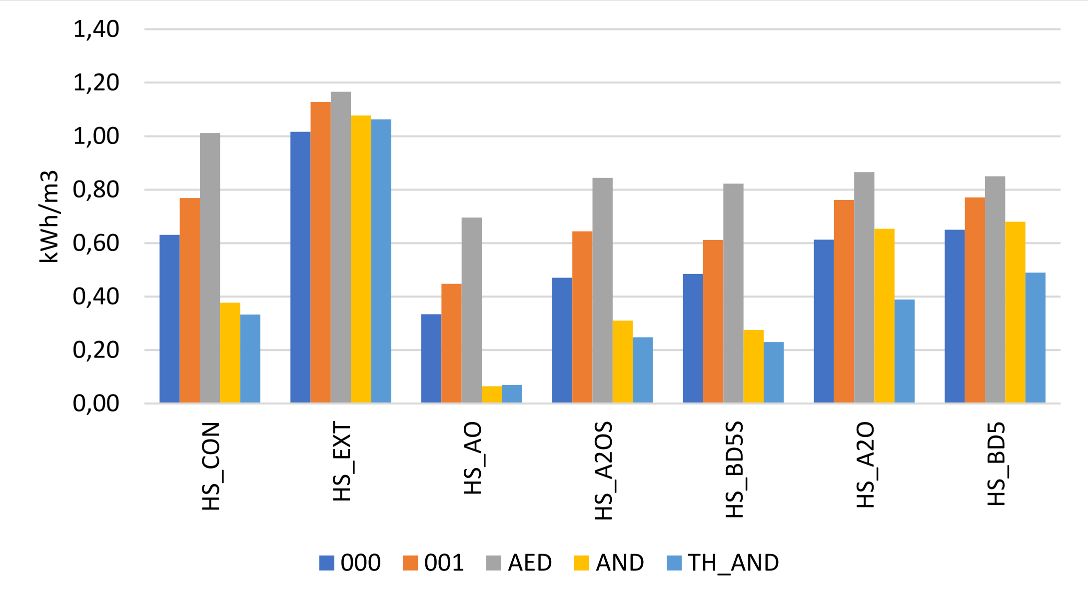

Figure 4-6 SEC2 Results for HS Wastewaters

Compared to the “No Action” option in sludge processing (S_X_00_000 cases), aerobic sludge processing increased specific energy usage significantly. This is due to the additional aeration needed for aerobic digester needs. SEC1 increased by up to 60% for conventional activated sludge process, 14% for extended aeration, 107% for A/O, 79% for A2O with primary sedimentation, 39% for A2O with no primary sedimentation, 70% for Bardenpho5 with primary sedimentation, and 30% for Bardenpho5 with no primary sedimentation depending on the strength of the wastewater. The inclusion of primary sedimentation in wastewater treatment that relies on A2O and Bardenpho5 decreased specific energy usage significantly. Similar trends are observed for SEC2 (Table 4-6). In extended aeration, aerobic stabilization increases SEC1 and SEC2 by up to 3% compared to dewatering and thickening only. However, if aerobic stabilization is applied, SEC1 and SEC2 increase dramatically compared to thickening and dewatering only (cases S_X_00_001). The highest increase would be for A/O (up to 53%) followed by conventional activated sludge (up to 33%). Aerobic stabilization results in up to 14% increase in SEC1 and SEC2 compared to thickening and dewatering only for A2O and Bardenpho5 with no primary sedimentation. Especially for A/O and conventional activated sludge, aerobic sludge stabilization can be costly, since the energy consumption of these treatment plants can double with aerobic sludge stabilization (Figure 4-7).

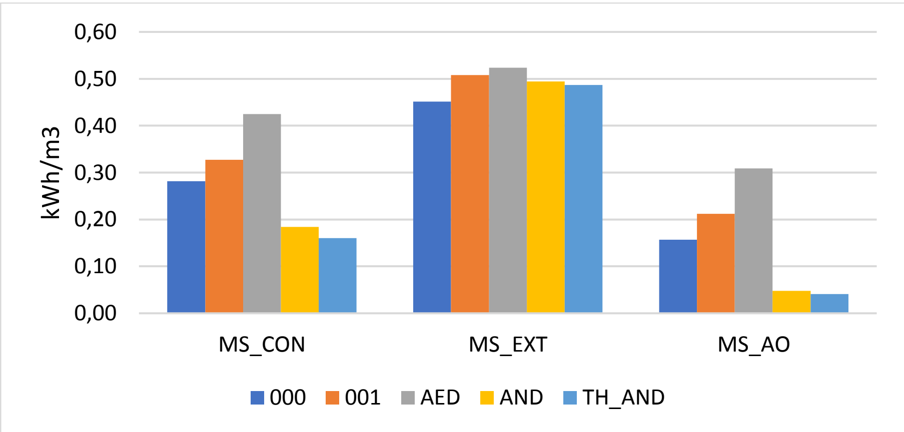

Figure 4-7 SEC1 Results of Conventional AS, Extended Aeration And A/O Processes for MS Wastewaters

On the other hand, anaerobic stabilization results in favorable SEC1 and SEC2 values for some of the treatment processes (Figure 4-5 & Figure 4-6). As energy produced during anaerobic stabilization can be partially substituted for the energy required by a treatment plant, lower specific energy usages can be obtained. For example, up to 81% less SEC1 and SEC2 were obtained for A/O compared to no sludge processing cases (S_AO_00_000) for different wastewater strengths. This value was up to 40%, 43%, and 43% for conventional activated sludge, A2O with primary sedimentation, and Bardenpho5 with primary sedimentation, respectively. When there was no primary sedimentation in A2O and Bardenpho5 treatment, anaerobic sludge stabilization did not provide an advantage in specific energy usage because of anaerobic digestion biogas production rates increase when primary sludge is introduced into the digester (Figure 4-8). For anaerobic sludge, stabilization was advantageous for A2O and Bardenpho-5 when thermal hydrolysis was applied as sludge pre-treatment (Carrère et al., 2010). Anaerobic stabilization of sludge did not decrease specific energy usage for extended aeration at levels compared to other treatment processes. Yet, lower SEC1 and SEC2 values were obtained compared to aerobic sludge stabilization of sludges produced through extended aeration.

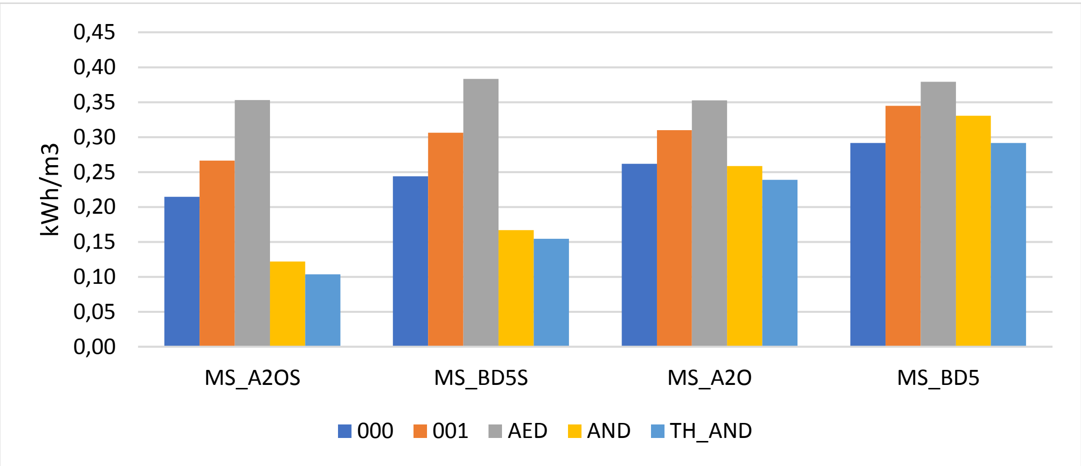

Figure 4-8 SEC1 Results of A2O And Bardenpho-5 Processes for MS Wastewaters

4.3.2. Result of Carbon Footprint Calculations

In this part of the study, hourly GHG emissions were calculated to represent the total carbon footprint of the models. It was seen that leading influencers of carbon footprint are direct emissions of N_2O and indirect emissions due to electrical consumption and sludge transportation. For 105 treatment models, it was observed that, on the average, carbon footprint arises 31% from N_2O emissions, 28% from electrical consumption and 33% from sludge transportation. The carbon footprints of the models are provided in Table 4-7 and Figure 4-9.

Table 4-7 Carbon Footprint Result Table

Model Name	GHG Emissions (kgCO_2eq/h)						
	Treatment Process (X)						
High Strength	**CON**	**EXT**	**AO**	**A2OS**	**BD5S**	**A2O**	**BD5**
HS_X_00_000	4,765	5,538	3,670	5,059	5,688	3,388	3,437
HS_X_00_001	4,945	5,697	4,026	5,092	5,775	3,751	3,239
HS_X_00_AED	4,433	5,620	3,706	4,722	4,039	3,563	3,097
HS_X_00_AND	4,673	5,643	3,225	4,268	5,201	3,180	2,728
HS_X_TH_AND	4,539	5,624	4,192	4,488	5,530	2,747	2,404
Medium Strength	**CON**	**EXT**	**AO**	**A2OS**	**BD5S**	**A2O**	**BD5**
MS_X_00_000	1,801	1,669	1,881	2,914	2,889	2,284	2,038
MS_X_00_001	1,878	1,781	2,083	2,897	2,961	2,184	2,092
MS_X_00_AED	1,673	1,742	1,906	2,717	2,805	2,113	2,008
MS_X_00_AND	1,528	1,730	1,663	2,460	2,688	1,968	1,814
MS_X_TH_AND	1,455	1,693	1,744	2,483	2,622	1,929	1,826
Low Strength	**CON**	**EXT**	**AO**	**A2OS**	**BD5S**	**A2O**	**BD5**
LS_X_00_000	1,048	947	864	1,188	1,124	974	996
LS_X_00_001	1,062	1,001	982	1,247	1,204	1,023	1,063
LS_X_00_AED	931	979	802	1,149	1,114	966	1,018
LS_X_00_AND	798	969	648	779	949	828	927
LS_X_TH_AND	682	951	588	749	946	806	972

For all wastewater strengths and sludge processing options, hourly GHG emissions ranged between 682 kgCO_2eq/h and 4,945 kgCO_2eq/h for conventional activated sludge, 951 kgCO_2eq/h and 5,697 kgCO_2eq/h for extended aeration, 588 kgCO_2eq/h and 4,192 $kgCO_2eq/h$ for A/O, 749 $kgCO_2eq/h$ and 5,092 $kgCO_2eq/h$ for A2O with primary settling, 806 $kgCO_2eq/h$ and 3,751 $kgCO_2eq/h$ for A2O with no primary settling, 946 $kgCO_2eq/h$ and 5,775 $kgCO_2eq/h$ for Bardenpho5 with primary settling, and finally 972 $kgCO_2eq/h$ and 3,437 $kgCO_2eq/h$ for Bardenpho5 with no primary settling (Table 4-7). For all ranges given for a specific treatment process, combinations that do not include sludge stabilization have the highest carbon footprint values. The lowest carbon footprint values were obtained from cases where thermal hydrolysis and anaerobic digestion were used for sludge processing. Compared to the only thickening and dewatering cases (S_X_00_001 cases), aerobic digestion (S_X_00_AED cases) decreases carbon footprint by 16% for conventional activated sludge process, 2% for extended aeration, 25% for A/O, 23% for A2O with primary sedimentation, 15% for A2O with no primary sedimentation, 13% for Bardenpho5 with primary sedimentation, and 14% for Bardenpho5 with no primary sedimentation. These represent the averages for the three strengths of the wastewater.

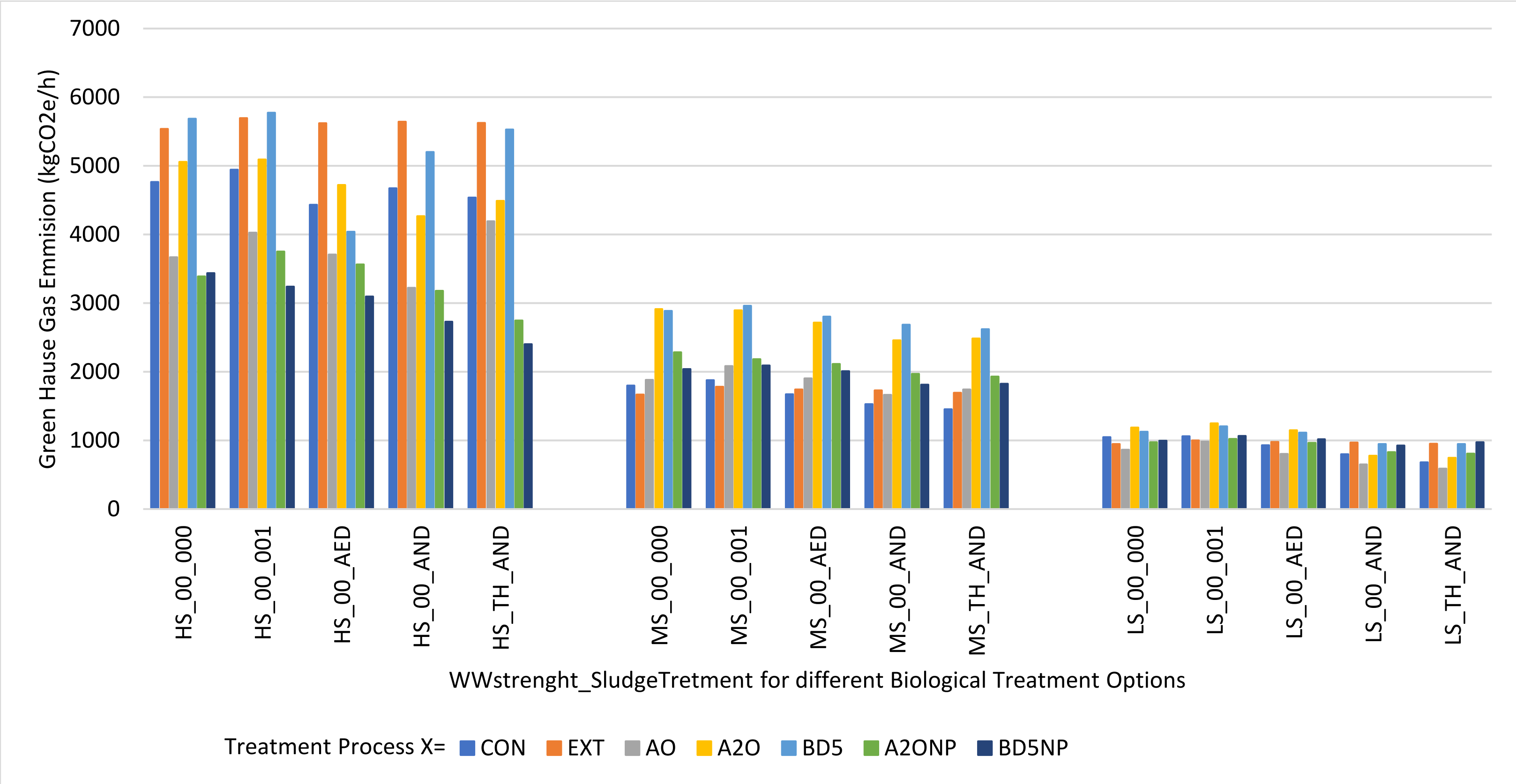

Figure 4-9 Carbon Footprint Results Graph

Compared to the only thickening and dewatering cases in sludge processing (S_X_00_001 cases), anaerobic digestion (S_X_00_AND cases) decreases carbon footprint by 11% for conventional activated sludge process, 2% for extended aeration, 12% for A/O, 7% for A2O with primary sedimentation, 5% for A2O with no primary sedimentation, 14% for Bardenpho5 with primary sedimentation, and 4% for Bardenpho5 with no primary sedimentation average for the three strength of the wastewater .

Lastly, compared to only thickening and dewatering for sludge processing (S_X_00_001 cases), thermal hydrolysis and anaerobic digestion (S_X_TH_AND cases) decreases carbon footprint by 22% for conventional activated sludge process, 4% for extended aeration, 17% for A/O, 22% for A2O with primary sedimentation, 20% for A2O with no primary sedimentation, 12% for Bardenpho5 with primary sedimentation, and 16% for Bardenpho5 with no primary sedimentation average for the three strengths of the wastewater .

It was observed that unlike specific energy consumption, the carbon footprint trends are changing among wastewater strengths (*Figure 4-9*). The reason for the trend change observation is arising from the change of N_2O emissions both for the treatment and the sludge stabilization options and most importantly for wastewater strengths. The GHG emissions contributors are provided in Appendix E between Table E-1 and Table E-7.

For high strength wastewaters, the N_2O emissions were observed to be dominating the total carbon footprint. The carbon footprint arising from N_2O emissions is climbing up to 50% of the total footprint for HS wastewaters. Additionally, it can be stated that in HS wastewaters A2O and Bardenpho-5 without primary sedimentation treatment options have the lowest carbon footprints. Therefore, it can be deducted that in HS wastewaters advance nitrogen removal is strongly suggested for low carbon footprint operation. On the other hand, it can be stated that traditional technologies (conventional AS and extended aeration) have the lowest carbon footprint for MS wastewaters. Lastly, the carbon footprint implications for HS and MS wastewaters are not valid for LS wastewaters. It was observed that N_2O emissions are no longer the main influencer for carbon footprint for LS wastewaters. The carbon footprint of the N_2O emissions drops down to 8% in total footprint. It can be stated that indirect emissions are the main influencers of the carbon footprint for LS wastewaters. The GHG arising from electrical consumption and sludge transportation contributes 43% and 40% of the total carbon footprint for LS wastewaters. Moreover, for LS wastewaters, it was observed that A/O process has the lowest carbon footprint due to the lowest electrical consumption. Average GHG contributions to total carbon footprint for different wastewater strengths are provided in Figure 4-10.

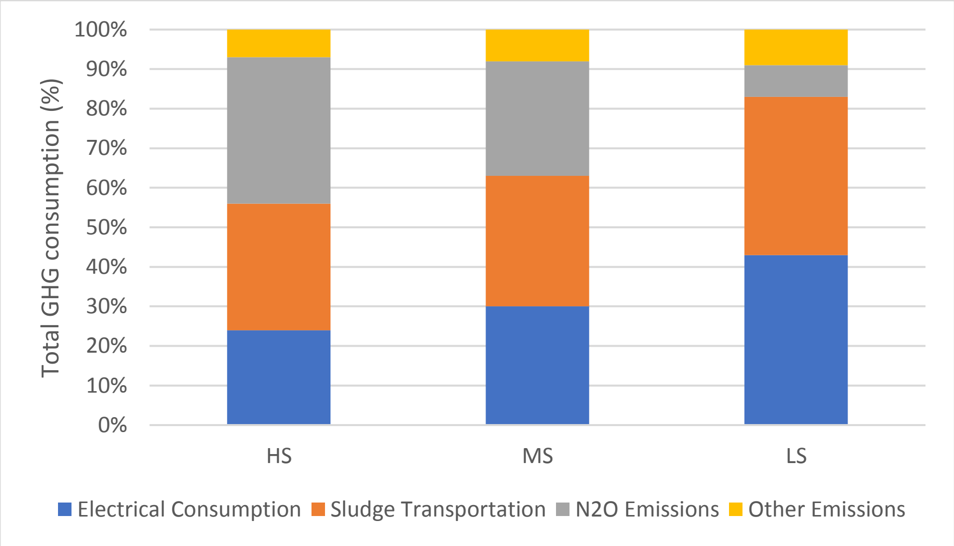

Figure 4-10 GHGs Average Contribution to The Total Carbon Footprint for Different WW Strengths

4.3.3. Result of Cost Calculations

Capital and operational costs were calculated for all created models and used to calculate the NPV for 20 years serving period. In the models of no sludge processing (S_X_00_000), it was calculated that money spent on volumetric waste sludge transportation is unrealistically high. Therefore, it was deducted that calculated NPVs of these models are not representing a feasible calculation. The NPVs of the models are provided in Table 4-8.

Table 4-8 20-Years NPV Results

Sludge Treatment	20 years NPV (MTL)						
	Treatment Process (X)						
High Strength	**CON**	**EXT**	**AO**	**A2OS**	**BD5S**	**A2O**	**BD5**
HS_X_00_001	236	291	163	215	201	223	258
HS_X_00_AED	264	297	224	239	279	235	280
HS_X_00_AND	120	289	138	146	134	208	240
HS_X_TH_AND	140	319	179	184	176	239	252
Medium Strength	**CON**	**EXT**	**AO**	**A2OS**	**BD5S**	**A2O**	**BD5**
MS_X_00_001	124	173	99	120	131	128	142
MS_X_00_AED	144	177	133	152	165	148	161
MS_X_00_AND	72	176	87	81	98	113	138
MS_X_TH_AND	85	189	134	106	127	134	166
Low Strength	**CON**	**EXT**	**AO**	**A2OS**	**BD5S**	**A2O**	**BD5**
LS_X_00_001	73	105	64	77	84	77	86
LS_X_00_AED	84	108	67	85	103	82	100
LS_X_00_AND	37	106	42	54	63	70	82
LS_X_TH_AND	42	117	66	67	92	84	116

For all wastewater strengths and sludge processing options, 20 years NPVs were ranged between 37 MTL and 264 MTL for conventional activated sludge, 105 MTL and 319 MTL for extended aeration, 42 MTL and 224 MTL for A/O, 54 MTL and 239 MTL for A2O with primary settling, 70 MTL and 239 MTL for A2O with no primary settling, 63 MTL and 279 MTL for Bardenpho5 with primary settling, and finally 82 MTL and 280 MTL for Bardenpho5 with no primary settling.

A scatter graph of capital cost versus NPV was prepared (Figure 4-11). On that graph, it was observed that anaerobic stabilization processes (S_X_00_AND and S_X_TH_AND) are concentrated in a different region. The reason for that can be stated as the anaerobic stabilization processes having a significant capital cost where anaerobic digestion, combined heat and power, and thermal hydrolysis units have distinguished capital cost.

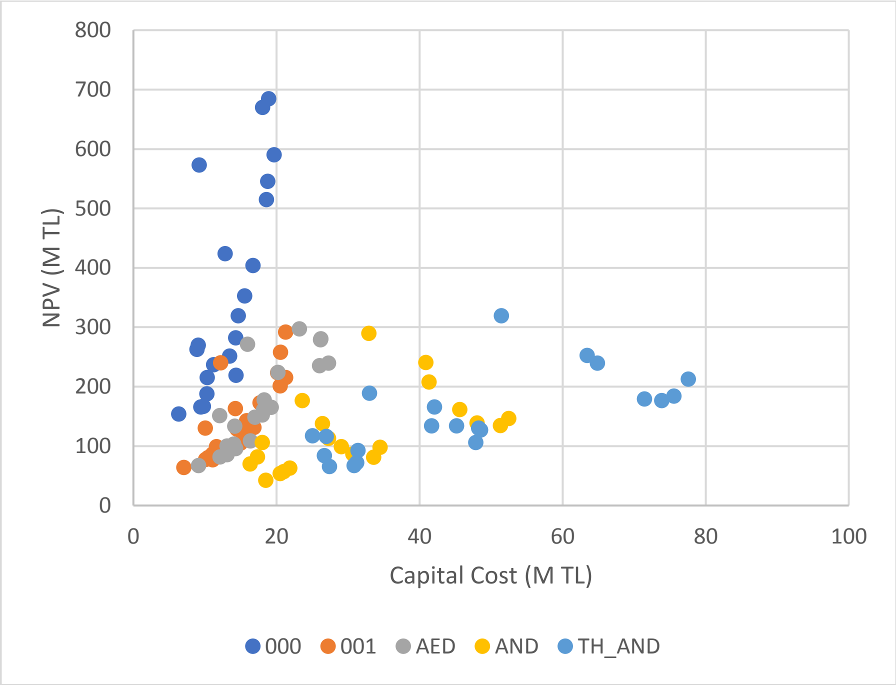

Figure 4-11 NPV to Capital Cost Scatter Graph

For a better understanding of NPV reduction of anaerobic stabilization processes, investment cost and NPV changes were investigated. It was assumed that thickening and dewatering (S_X_00_001 cases) sludge treatment option is the default for all treatment plants. Additionally, the capital cost difference between anaerobic digestion (S_X_00_AND) and thickening and dewatering (S_X_00_001) and the cost difference between thermal hydrolysis with anaerobic digestion (S_X_TH_AND) and thickening and dewatering (S_X_00_001) were assumed to be the investment cost of that anaerobic sludge process. Moreover, NPV changes of these investments were calculated. If the NPV change is equal to zero, it can be assumed that the investment cost compensates itself in 20 years. If the NPV change is below zero, it can be said that the investment cost already compensated its value before the 20 years serving period is reached. The results are provided in Table 4-9.

Table 4-9 AD and Thermal Hydrolysis Investment Cost to NPV Analysis Table

WW Strength (S)	HS		MS		LS	
Model Name	**Investment Cost (MTL)**	**NPV (20 years) Change (MTL)**	**Investment Cost (MTL)**	**NPV (20 years) Change (MTL)**	**Investment Cost (MTL)**	**NPV (20 years) Change (MTL)**
S_CON_00_AND	33.42	-78.74	19.04	-30.96	10.54	-23.71
S_CON_TH_AND	65.37	-27.47	38.21	0.14	20.74	-8.96
S_EXT_00_AND	11.62	-2.13	5.91	3.67	3.05	1.07
S_EXT_TH_AND	30.18	27.75	15.29	16.15	10.08	12.53
S_AO_00_AND	33.76	-24.30	19.05	-12.34	11.42	-21.38
S_AO_TH_AND	57.16	16.22	33.55	34.92	20.33	2.05
S_A2OS_00_AND	31.17	-69.05	18.19	-38.85	9.44	-23.01
S_A2OS_TH_AND	54.27	-31.30	32.46	-14.39	19.78	-9.73
S_BD5S_00_AND	30.81	-66.93	17.63	-33.67	9.86	-21.19
S_BD5S_TH_AND	53.35	-25.08	31.69	-4.46	19.35	8.25
S_A2O_00_AND	21.20	-15.54	12.77	-15.51	6.20	-7.51
S_A2O_TH_AND	44.75	16.09	27.18	5.63	16.58	6.46
S_BD5_00_AND	20.30	-17.30	10.63	-4.72	6.27	-4.39
S_BD5_TH_AND	42.86	-5.66	26.28	23.38	15.91	30.04

In Table 4-9, minus changes in NPV are green highlighted. The green highlighted results show the models that have reduced the NPV value within 20 years of service. It was observed for HS wastewaters that TH process with extended aeration, A/O and A2O without primary sedimentation could not compensate the investment cost in 20 years serving period. All other anaerobic digestion implementations compensate their investment cost in at most 20 years for HS wastewaters. On the other hand, it was observed for MS wastewaters that extended aeration could not achieve any profit in 20 years. All the anaerobic digestion implementations without pre-treatment compensate their investment cost. And, for TH processes, only Bardenpho-5 and A2O with primary sedimentation system could compensate the investment cost in MS wastewaters. Lastly, for LS wastewaters, the results show similarities with MS wastewaters processes. It can be deducted from positive values that the 20 years serving period is not enough to compensate for the investment cost of these highly budget units. However, for MS and LS wastewaters, it can be said that Bardenpho-5 and A2O processes without primary sedimentation, thermal hydrolysis implementation is not feasible. This is because, cost of chemical addition is needed to meet effluent TP concentrations, which increases with TH implementation, is greater than the cost of energy saved by anaerobic digestion.

4.4. Conclusions

In this study, 105 treatment scheme combinations were created as BioWin models. All the created model’s energy consumption, carbon footprint and costs in net present values were calculated.

It was observed that A/O process’s energy consumption is the lowest among other treatment options. Among the sludge stabilization methods, it can be stated that anaerobic digestion and thermal hydrolysis units have the lowest energy consumption of the treatment options.

It was observed that the carbon footprint's main influencers are changing for different wastewater characteristics. It can be stated that among all treatment options, A2O and Bardenpho-5 without primary sedimentation have the lowest carbon footprint for HS wastewaters. Moreover, it was calculated that conventional AS has the lowest carbon footprint for MS wastewaters. Lastly, it was calculated that A/O process has the lowest carbon footprint for LS wastewaters.

It was observed that the NPV of the models is highly affected by operational costs (electrical consumption) of the facilities. On the other hand, it was deducted that even with high inflation rate, costly units like anaerobic digestion, combined heat and power unit, and thermal hydrolysis have potential to compensate their investment costs in 20 years period.

In conclusion, if the best scheme should be proposed, low SRT and using diffusers for aeration can be combined with anaerobic digestion with struvite recovery could be the ultimate municipal WWTP scheme in terms of carbon footprint and energy consumption. To explain, it can be said that treatment system with low SRT (conventional AS, A/O) with anaerobic digestion is requiring the least amount of energy need. Moreover, in Chapter 3, it was observed that anaerobic digestion sludge stabilization methods have the lowest sludge outputs. Lastly, with struvite recovery addition some the waste activated sludge could be used for land application which prevents the waste activated sludge turns into GHG emissions. Yet, the solution may not be used for nitrogen sensitive receiving body environment.

It should be noted that energy consumption, carbon footprint and NPVs of WWTPs can be compared with the help of this study. For existing treatment plants, a modeling and optimization study can potentially lower the carbon footprint and energy consumption of the system significantly. Moreover, energy reduction should also potentially lower the NPV of the existing system. In this regard, a modeling optimization study for a real WWTP was presented in the following chapter (Chapter 5).

CHAPTER 5

SIMULATION-BASED IMPROVEMENT OF THE OPERATION OF A WASTEWATER TREATMENT PLANT IN BURSA, TURKEY

5.1. Introduction

Electrical consumption in wastewater collection and treatment vary from 1% to 5% of the overall electricity consumption of countries (Longo et al., 2016). It is expected that the share may increase with the increasing number of WWTPs in the world. Therefore, the total energy consumption and energy efficiency of a WWTP are important. Money spent to achieve energy consumption reduction can be considered as a non-zero-sum game because the energy-saving can compensate for the initial cost over time. A study shows that DO concentration optimization in bioreactors can save up to 10% of energy usage. Additionally, optimization of pump rotating speeds can save up to 6% of the energy usage (Wei, 2013).

Unfortunately, there are no solid standards to evaluate the energy performance of a WWTP. The Horizon program is trying to establish an energy performance grade system for WWTPs with the help of four European countries with nine partner companies (ENERWATER, 2019). Energy usage optimization is not only budget-friendly but also helps to reduce indirect carbon footprint. N_2O, CH_4, and CO_2 gas emissions from WWTPs could account for 50% of the total carbon footprint of a WWTP (Mannina et al., 2019).

The aim of this paper is to simulate the operation of a real WWTP plant to examine its energy consumption and carbon footprint through modeling. Impacts of various management options on energy usage and carbon footprint were evaluated. Modeling was used as a tool to analyze the impact of operational as well as treatment process changes on the performance of the WWTP as such modifications in an already-installed facility cannot be done on a trial-and-error basis.

5.2. Description of the Study Site

The study was performed for Bursa East WWTP located in Küçük Balıklı district (Figure 5-1). The WWTP was completed and put in service in April 2006 (BUSKİ, 2018). The plant covers an area of 516,619 m^2 and serves an approximate population equivalent of 1,550,000. The average design flow is 240,000 m^3/day and the plant is designed to serve a capacity of 320,000 m^3/day in 2030.

Figure 5-1 Bursa East Municipal WWTP (BUSKİ, 2018)

The treatment process in the facility is Bardenpho-5 process with an oxidation ditch configuration, as stated by plant management (Personal Communications, 2019). The process aims to remove suspended solids, organic carbon, nitrogen and phosphorus from the wastewater by biological treatment.

Raw wastewater enters the treatment plant from an intake chamber. Then screen units remove coarse particles from the wastewater. After screening, three screw pumps are elevating the wastewater. The pumps are delivering the wastewater to the grit chambers. After grit chambers, wastewater is elevated through screw pumps again.

The second pump station delivers the wastewater to a selector tank. After the selector tank, wastewater enters a Bardenpho-5 process with oxidation ditch configuration (BUSKİ, 2018).

The sludge produced as a by-product of treatment is first introduced into a sludge buffer tank which is aerated to control P release. Afterward, sludge is processed in belt thickeners and then dewatered using centrifugal decanters. Lime stabilization is applied and finally the sludge is completely combusted. The facility is owned by Bursa Water and Sewerage Administration but operated by Kuzu Group. Sludge combustion unit, on the other hand, is managed separately (BUSKİ, 2018).

The general wastewater treatment process flow diagram is shown in Figure 5-2. In the plant; there are three parallel wastewater lines, each including four oxidation ditch bioreactors (ODs) as stated by plant management (Personal Communications, 2019). Each line contains four secondary clarifiers (Figure 5-3). When the ODs are named left to right as OD1, OD2, OD3 and OD4, Bardenpho-5 process is achieved in the following order; anaerobic tank, prim-anoxic (OD2), aerobic (OD1 followed by OD3) and secondary anoxic with re-aeration (OD4). ODs, flow directions between tanks (shown by arrows) and wastewater inlet and outlet points (bold arrows) are provided in Figure 5-4.

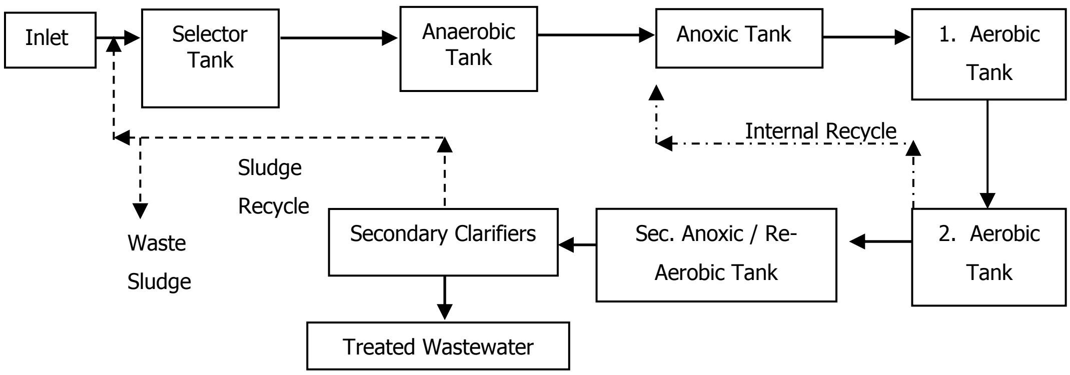

Figure 5-2 Wastewater Treatment Process Flow Diagram of Bursa East Municipal WWTP

Figure 5-3 Top View of the Process Lines in the WWTP

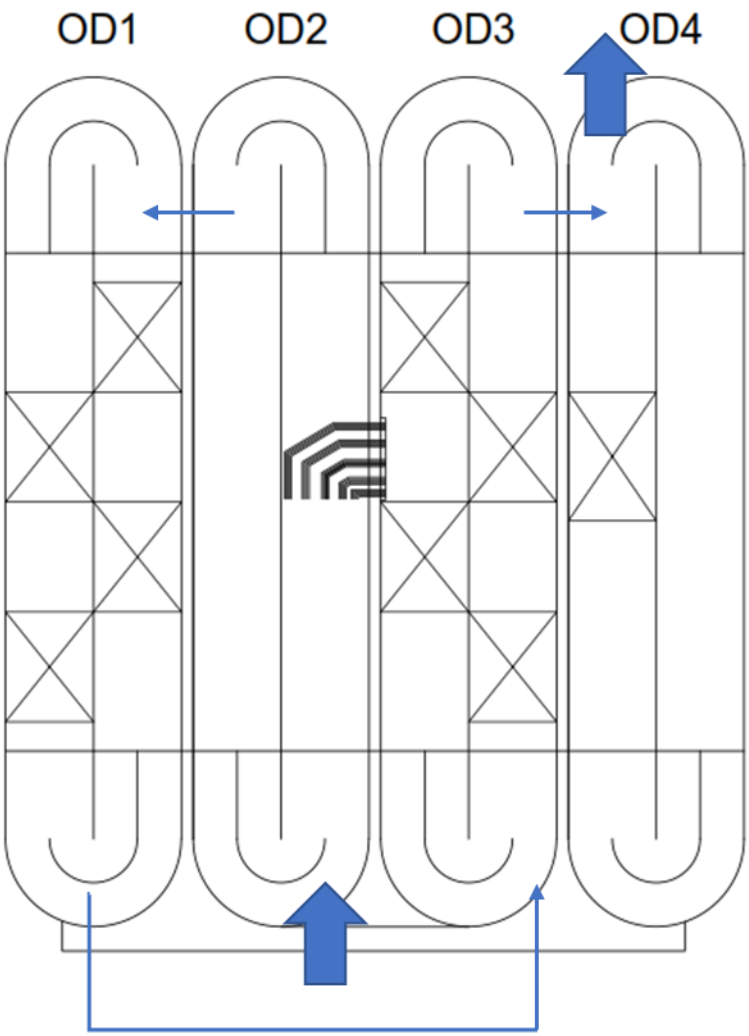

Figure 5-4 Oxidation Ditch Bioreactors Configuration of Bursa East WWTP

5.3. Methodology

In this study, simulation modeling of Bursa East WWTP was carried out by using BioWin 5.3 simulation software. BioWin 5.3 developed by EnviroSim Associates is used for modeling of the WWTP. BioWin is a well-established software that can be used to design, upgrade, and optimize all types of WWTPs with physical, biological, and chemical process models (EnviroSim, 2019).

The model was calibrated with 2017 annual average data and validated for 2017 monthly average data. By using the calibrated model, it is possible to assess the energy consumption and the carbon footprint of the facility. Different management alternatives were simulated to suggest improvements in the operation of the WWTP in terms of energy consumption and carbon footprint.

The steps followed in the modeling study are provided below;

5.3.1. Determination of Influent Wastewater Characteristics

Raw wastewater characteristics were obtained from Bursa East WWTP. The design stage reactor volumes were also obtained from the website of the BUSKİ. The raw wastewater and biomass parameter values used in the design of the WWTP are listed in Table 5-1 (BUSKİ, 2018). Minimum effluent concentrations are stated in the website of BUSKİ which provided in Table 5-2 (BUSKİ, 2018). Design parameter values may not represent current observed values in the facility currently. Therefore, the annual average of influent characteristics was also obtained for 2017. Due to absence of daily data of the plant, the dynamic solution capability of the model was not utilized.

Table 5-1 Design Parameters of Bursa East WWTP

Parameters	Unit	Value
COD_{in}	mg/L	533
TN_{in}	mg/L	63
TP_{in}	mg/L	11
DO_{in}	mg/L	0
Alkalinity	$mgCaCO_3/L$	350
Fbs, rbCOD/TotalCOD	%	24
Fup - Unbiodegradable particulate COD/total COD	%	13
Fus - Unbiodegradable soluble COD/total COD	%	5
FNA - Ammonia gNH3-N/gTKN	%	75
Fnus - Soluble Unbiodegradable TKN	%	3
Incoming WW Flowrate	m^3/d	240,000
Particulate substrate COD:VSS ratio	mgCOD/mgVSS	1.48
FupP - P:COD for unbiodegradable part	mgP/mgVSS	0.015
VSS/TSS	mgVSS/mgTSS	0.65

Table 5-2 Discharge Standards (BUSKİ, 2018)

Parameters	Discharge Standards (mg/L)
BOD	25
COD	125
TSS	35
TN	10
TP	3

Wastewater influent characteristics, sludge retention time (SRT), recycled activated sludge (RAS), waste activated sludge (WAS) and internal recycle (IR) values, representing annual average of 2017 are provided in Table 5-3.

Table 5-3 2017 Annual Average Values of Bursa East WWTP for 2017 (Personal Communications, 2019)

	Values	Units
Flow	249,000	m^3
COD	642	mg/l
TN	58	mg/l
TP	9.1	mg/l
pH	8.04	mg/l
IR	1,140,000	m^3
RAS	255,000	m^3
WAS	10,000	m^3

5.3.2. Treatment Plant Layout Build

Units and processes applied in the plant are configured as a process flow diagram in the model. Two different approaches were employed for system configuration in BioWin. In the first one, the system is configured as a single-line as depicted in Figure 5-5. In the second one, the system consists of three parallel-line as shown in Figure 5-6 to represent the exact numbers of units (Figure 5-2) in the WWTP. In running the system as a single line as in Figure 5-5, cumulative unit/tank volumes were considered. Therefore, in both configurations, the total volumes of a given process are the same.

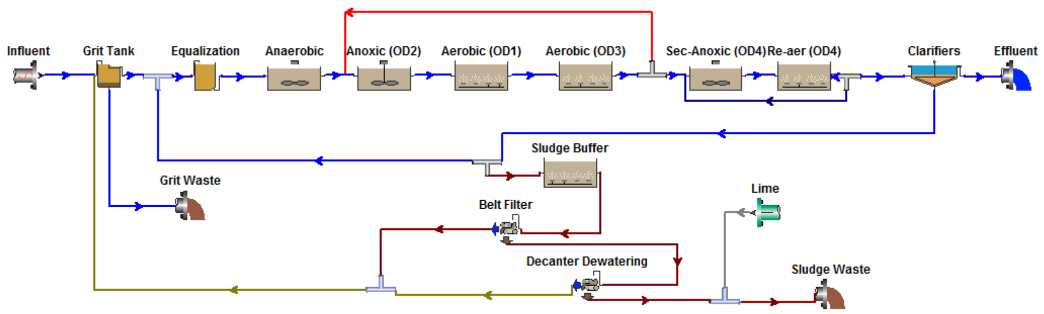

Figure 5-5 Single-Line Configuration

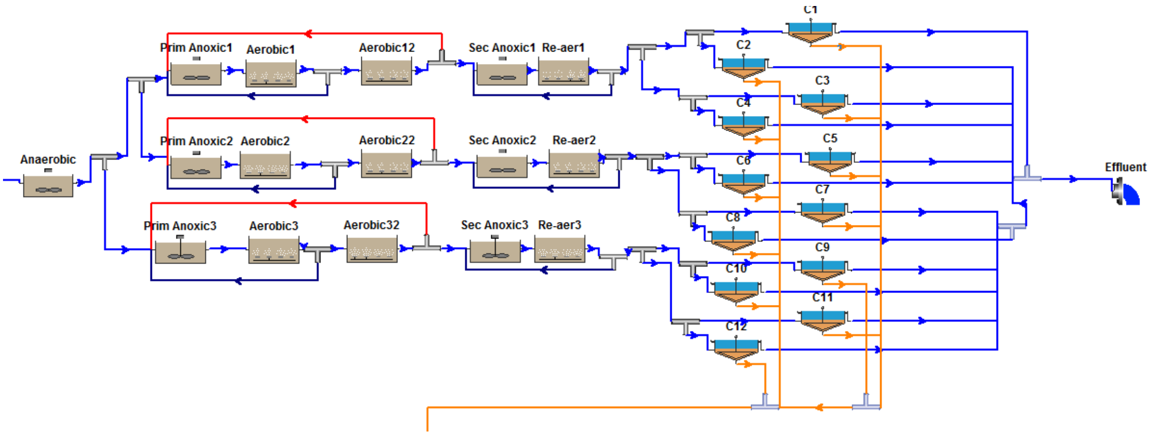

Figure 5-6 Parallel-Line Configuration

In simulations, it was noticed that using the parallel line configuration did not affect the effluent characteristics. Therefore, for simplicity, model studies had continued with single-line configuration. Following system configuration in BioWin, all physical and other parameter inputs were placed within the configuration through input windows and sheets of BioWin. The inputs of the model were obtained from Bursa East WWTP (Personal Communications, 2019). Moreover, the facility was visited on July 11, 2018, and authorities were interviewed to ensure the accuracy of the information gathered through a literature search. In addition, the annual report of 2017 prepared for the facility was examined to obtain up-to-date operational data (Personal Communications, 2019). Total volumes of bioreactors are provided in Table 5-4.

Table 5-4 Unit Volumes of Bioreactors

Section Name	Unit	Value
Selector Tank Volume	m^3	4,408
Anaerobic Tank Volume (2 Lines in Total)	m^3	33,94
1. Anoxic Tank Volume (3 Lines in Total)	m^3	72,123
1. Aerobic Tank Volume (3 Lines in Total)	m^3	144,247
2. Anoxic Tank Volume (3 Lines in Total)	m^3	52,65
2. Aerobic Tank Volume (3 Lines in Total)	m^3	19,473
Aerobic Reactor Total Volume (3 Lines in Total)	m^3	288,493
Total Biological Reactor Volume (Line 1/2/3 + Anaerobic+Selector)	m^3	326,841

Five different pump stations were placed in the model to represent pumps in the facility (Personal Communications, 2019). These pump stations can be listed as;

- Inlet pump station I (After screens)
- Inlet pump station II (After grit chamber)
- IR pump station
- RAS pump station
- WAS pump station

5.3.3. Sensitivity Analysis

Model inputs are relatively complicated and broad in number, often accommodating various components that are not measured in WWTPs (Dursun et al., 2011). BioWin software has numerous inputs. To illustrate; there are 20 wastewater influent characteristics, 101 kinetic, 94 stoichiometric, and five settling-related parameters. Moreover, there are other parameters for power calculations. In order to find sensitive parameters, a sensitivity analysis was conducted for a total of 57 selected parameters involving 12 wastewater fraction, 8 stoichiometric, 1 temperature, 30 kinetic and 6 solid separation.

5.3.4. Calibration and Validation

A model has to be calibrated and validated to a system before it can be used for a purpose. In calibration, biological, chemical, and kinetic parameters were tuned to provide an agreement between the simulated and observed (measured) values; i.e. effluent concentrations following treatment. At the validation step, the validity of the calibrated parameter values for new conditions was tested. Upon successful calibration and validation, a model can be used to make predictions about potential improvements or changes in system outputs due to changes in processes or influent concentrations.

In the calibration of the model, below equations (Equation 11-13) were used to check the accuracy level of predictions. The performance of the model in predicting treatment performance was based on treatment levels in different water quality parameters. The aim of the calibration was to reduce the difference between observed and predicted treatment levels. Errors were calculated for COD, BOD, TSS, TP and TN removal efficiencies.

$$\mathrm{To} = \mathrm{Co_i} - \mathrm{Cf_i} \tag{11}$$

$$\mathrm{Tp} = \mathrm{Co_i} - \mathrm{Cp_i} \tag{12}$$

$$\mathrm{E} = \frac{|\mathrm{To} - \mathrm{Tp}|}{\mathrm{To}} * 100 \tag{13}$$

Where

To = Observed removal in constituent i (mg/L)

Co_i = Initial influent concentration in constituent i (mg/L)

Cf_i = Observed effluent concentration in constituent i (mg/L)

Tp = Predicted removal in constituent i (mg/L)

Cp_i = Predicted effluent concentration in constituent i (mg/L)

E = error in model prediction of treatment level (%)

The BioWin software is providing default wastewater fractions. On the other hand, there are available influent wastewater fractions of the treatment plant from the design stage of the facility. In order to understand which of these fractions are more suitable to simulate the plant, the given fractions and default fractions that Biowin software provides were tested for calibration.

Biowin software can handle dissolve dissolved oxygen (DO) in aerobic bioreactors with two different options. These are fixing the DO amount in the bioreactor or entering the airflow rate into the bioreactor. Since both input data are available for Bursa, it was decided to test these two different inputs for DO calculation of the model to check which option would provide a batter calibration.

Placement of diffusers and their impact on DO distribution is not homogeneous in oxidation ditches (ODs). Therefore, volumes of aerobic zones in the ODs were thought to be non-homogeneous. In calibration of the model, different volumes and locations were considered for aerated volumes for OD bioreactors.

After model calibration was completed, the calibrated model was validated for the monthly average values of five effluent parameters (COD, BOD, TSS, TN and TP) and energy consumption observed in 2017. The target accuracy of the model predictions compared to observed results was taken as 5% error in removal efficiencies of the effluent parameters and 10% error in energy consumption

5.3.5. Energy Consumption and Carbon Footprint

Energy consumption and carbon footprint of the facility were calculated. For energy consumption, BioWin results were used. The BioWin software enables power consumption analyses of an identified model if relevant inputs are provided. In *"Power Table"* of the software, energy consumption per hour can be accessed for blowers, mixing, pumping and solid/liquid separation.

For 2017, the authorities stated that the facility had 5242 kWh average daily energy consumption. Most energy-consuming operators are blowers and pumps. The most energy-consuming unit operators are listed in Table 5-5.

Table 5-5 Unit Base Daily Energy Consumption

Operators	Average Daily Consumption (kWh)
Blowers	2869.7
Mixers	219.6
Pumps	1396.8
Thickening & Dewatering	322.9

The energy consumption of the model was calibrated for the most energy-consuming unit operators. The validation was performed with eight monthly observed data. The targeted accuracy of the model predictions compared to the observed results is 10% error for energy consumption results.

In order to calculate the total carbon footprint of the treatment plant, direct and indirect GHG emissions were assumed to constitute the total carbon footprint of the facility (Ashrafi et al., 2014). In calculation of the direct carbon footprint, CO_2, CH_4 and N_2O emission rates from each bioreactor were multiplied with the volume of the bioreactors. Then, CH_4 and N_2O were converted into CO_2 equivalence. These gasses have 25 and 298 times higher GWP than CO_2, respectively (US EPA, 2016). Indirect emissions were calculated from the total energy consumption of the facility by using weighted carbon emissions per 1 kWh electricity production of Turkey which was calculated as 540 gCO_2eq/kWh (POSTNOTE, 2006). Since there is no observed data for carbon footprint of the system, the carbon footprint results could not be validated.

5.4. Results and Discussions

In the model simulation study, it was observed that setting the model with parallel lines has no impact on discharge values. Therefore, a single wastewater line model was accepted for practice.

5.4.1. Sensitivity Analyses

Sensitivity analyses were conducted for a total of 57 selected parameters. Some of the parameters can be described as sensitive; however, most of the sensitive parameters affect one or two of the effluent parameters. The parameters changing the effluent values more than 3% were considered as sensitive parameters that can alter the effluent concentrations of the system in calibration. These parameters are listed in Table 5-6. The results of the sensitivity analyses are listed in Appendix F between Table *F-1* and Table *F-3*.

Table 5-6 Sensitive Parameters

Sensitive parametres	Parametre Location	Change in Parameter	Affected Component	Component change (%)
FBS - readily biodegradable gCOD/Total COD	Raw wastewater fraction	+1%	TN	-14.73
		-1%		17.12
Fus - Unbiodegradable soluble COD/total COD	Raw wastewater fraction	+1%	COD	6.83
		-1%		-6.82
P in endegeneous Residue	Stoichiometric	+1%	TP	-3.31
		-1%		3.31
Anoxic Hydrolysis factor	Common Microbial Kinetics	+1%	TP	-6.85
		-1%		7.19
Anoxic/anaerobic decay rate	PAOs Microbial Kinetics	+1%	TP	9.93
		-1%		-10.27
Percent Solid Removal of Clarifier	Settling Parameters	+1%	BOD, COD, TSS, TP, TN	Appendix F Table F-3
		-1%		

5.4.2. Calibration

<u>Model Calibration</u>

The system contains a total of twelve oxidation ditches. There are two challenges in simulating an oxidation ditch as a bioreactor. One of the challenges is the dilution occurring due to the cyclic motion of the wastewater in a single oxidation ditch. The other challenge is the extent of aerobic zones in aerobic bioreactors due to the placement of air diffusers. In a conventional aerobic bioreactor, the diffusers are located homogeneously. However, in Bursa East WWTP, the diffuser placement is not homogeneous in aerobic tanks. The diffuser placement is marked with blue color on the construction plan in Figure 5-7.

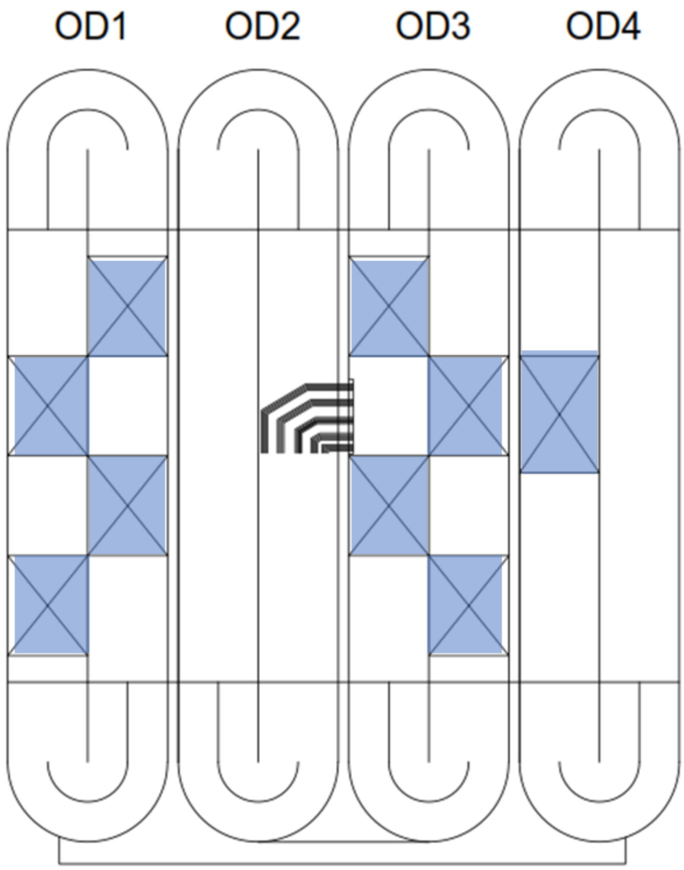

Figure 5-7 Picture taken from construction plan. Diffuser placement shown with blue boxes

In order to solve these challenges, the extent of aerobic zones was also considered in calibration. To address dilution factor and partial aeration, oxidation ditches were assumed to be divided into two tanks with an interior recycle. Interior recycle was assumed to provide cyclic motion in the oxidation ditch. For interior recycle ratio, it was also stated that the wastewater has a velocity of 0.3 m/s (Personal Communications, 2019). To obtain interior flowrate in a cubic meter per second (m^3/s), cross-sectional area (m^2) of the OD tank was multiplied with the velocity (m/s) of the wastewater.

One side width of the oxidation ditch is 15 and the water level of the tank was assumed to be at least 5m. Therefore, the cyclic motion area can be calculated as 225m^2. With 0,3 m/s velocity, the interior recycle flowrate was calculated as at least 67.5 m^3/s because the water level could be more than 5m (7m at maximum).

Only 28.5% of the oxidation ditch area is covered with diffusers. Since the DO is not dropping from 1.5 to 0 mg/l when wastewater leaves the aerated zone, the volumes of division also need to be estimated. For this matter, three options were considered such that 30%, 50% and 70% of the aerobic tanks are left as un-aerated. Only 50% option was selected for base model testing, due to the excessive error observed for other options. Modeled bioreactor configurations are illustrated in Figure 5-8. The best solution was found as assuming only 50% of the bioreactor's volume is aerated with an 85 m3/s interior flowrate between aerated and unaerated zones.

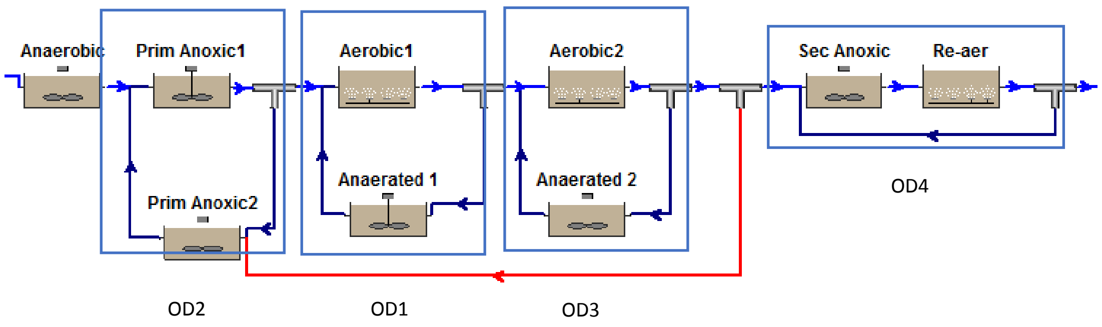

Figure 5-8 Oxidation Ditch Configuration

A set of given influent wastewater fraction parameters was available from the design stage of Bursa East Municipal WWTP. Therefore, given parameters versus parameters that BioWin software provides as default were also taken into consideration in calibration.

Given the above information, three variables, each has two different approaches, were combined to create eight different approaches for the model. The reason for testing all possible approaches is to understand the interference of the variables to each other. To illustrate, assuming all the bioreactor is aerated with air-flowrate definition and given parameters approach could be the best solution. Moreover, treatment errors were calculated for BOD, COD, TSS, TN and TP. Models were named to make the results understandable. The model naming for calibration is represented in Table 5-7.

Table 5-7 Model Naming Chart for Calibration

File Code	Oxidation Ditch Anoxic Volume
0	All the bioreactor is aerated
50	50% of the bioreactor is aerated
File Code	**Raw Wastewater Fractions**
Given	Fractions were taken from the facility
Default	Fractions BioWin software provides
File Code	**Air Flowrate**
BL	Air flowrate defined
DO	DO is setted

For model calibration, effluent parameter errors were normalized with the mean error of each effluent wastewater parameter. Thus, the parameter with the highest error will not affect the total cumulative error score alone. In the normalized error score, a value of 1.0 indicates the average error in the respective parameter. The normalized error scores are given in Table 5-8.

Table 5-8 Normalized Errors of Model for Calibration

Treatment Error Normalized Values	COD	BOD	TSS	TN	TP	Total Score
0_Default_BL	0.9	1.1	0.8	0.7	1.8	5.4
0_Given_BL	1.0	1.1	1.2	1.0	0.8	5.0
0_Default_DO	0.9	1.1	0.8	1.1	2.3	6.2
0_Given_DO	1.0	1.1	1.1	1.3	1.1	5.6
50_Default_BL	1.0	0.9	0.8	0.9	0.6	4.3
50_Given_BL	1.1	0.9	1.2	0.9	0.5	4.6
50_Default_DO	1.0	0.9	0.8	1.0	0.4	4.2
50_Given_DO	1.1	0.9	1.3	1.0	0.4	4.7

The best approach was selected as 50_Default_DO approach as it provided the least total normalized error. The selected approach is such that 50% of the aerobic tanks are assumed to be unaerated, default wastewater fractions that BioWin provided are used and DO is set to 1.5 mg/l in aeration zones. This model approach was selected for further calibration.

Sensitive Parameters and Secondary Clarifier Calibration

Two parameters were decided to be calibrated for the selected model approach. These parameters were unbiodegradable soluble COD to total COD ratio (FUS) from influent wastewater fractions and percent removal of secondary clarifier. The purpose of this calibration was to reduce the difference between model and observed data for COD and TSS effluents while the TN and TP values were tried not to be kept at target values. The value changes can be stated as 0.05 to 0.03 (Rössle et al., 2001) and 99.8% to 99.85% (Sanin et al., 2011) relatively. With this calibration, it was expected that errors in TSS and COD treatment efficiencies could be reduced.

Energy Consumption Calibration

Two energy inputs were decided to be calibrated for energy consumption. These inputs are the energy consumption of pumps and blowers since these operators are the most energy-consuming units of the facility (Table 5-5). On the other hand, mixing, thickening and dewatering units were also discussed in energy consumption calibration.

In BioWin simulation software the volumes of the bioreactors are set as constants. However, in the real case, the water level in the bioreactors can change with incoming flowrate variations. Therefore, the effect of flow variation on the mixer energy consumption could not be observed in simulated models. The energy consumption of mixing was assumed to be constant for any flow rate. On the other hand, thickening & dewatering, as well as energy consumption for pump operation, should be adjusted for a given flowrate. Moreover, energy consumption of pumps should be changed with the wastewater flow that passes through pumps. Lastly, blower energy consumption should be changed with incoming COD since the DO was set to 1.5 mg/L.

There are five pump stations placed in the model to represent the pumps in the facility. The total energy consumption of the pumps is known (Table 5-5). Each pump station's energy consumption was estimated and calibrated with defining the head and diameter values individually and compared with 2017 annual equipment operation energy consumption (Personal Communications, 2019). The model was slightly underestimating the power consumption of the air blowers compared to observed values. However, blower efficiencies cannot be defined in BioWin. In order to overcome this issue, the off-gas O_2 ratio was changed from 18.8% to 17.5%.

In the calibrated model with 2017 annual average inputs, the system consumes 5,203.92 kWh. In observed, for 2017 annual average was stated as 5,242.22 kWh. Additionally, the system has 9,659 $kgCO_2eq/h$ GHG emission. However, there is no monitored real data of GHG emissions of the facility to perform calibration and validation.

5.4.3. Validation

The influent parameters and observed effluent results used in validation are provided in Appendix G Table *G-1*.

Validation of Effluent Parameters

The validation results for 2017 monthly data are provided in Figure 5-9 to Figure 5-13.

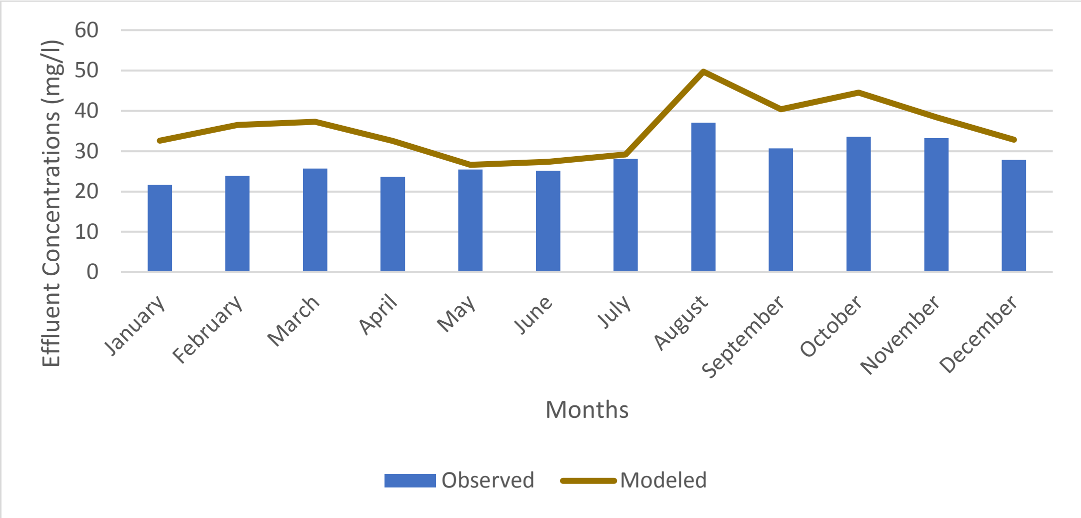

Figure 5-9 Effluent COD concentrations for 2017 Validation

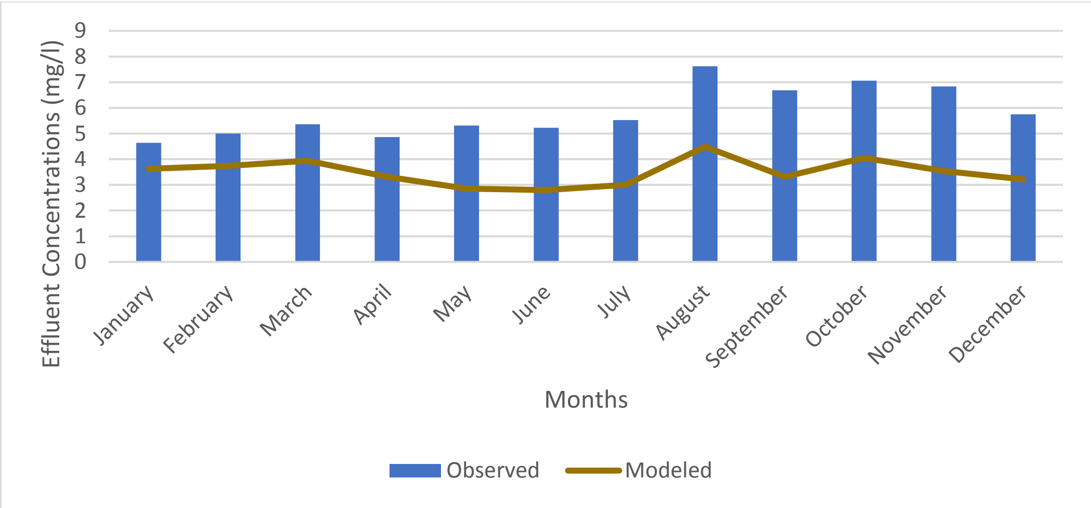

Figure 5-10 Effluent BOD concentrations for 2017 Validation

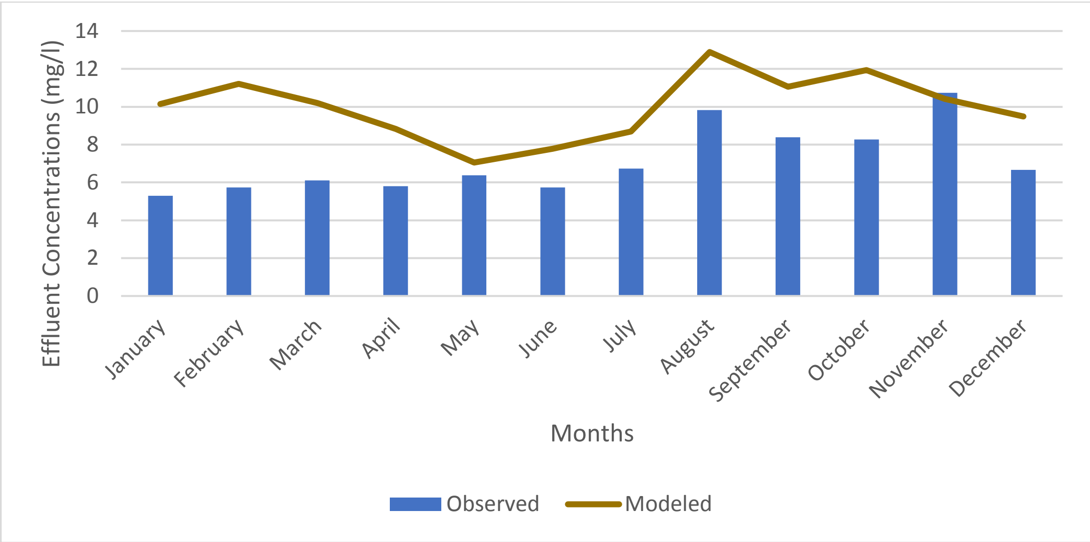

Figure 5-11 Effluent TSS concentrations for 2017 Validation

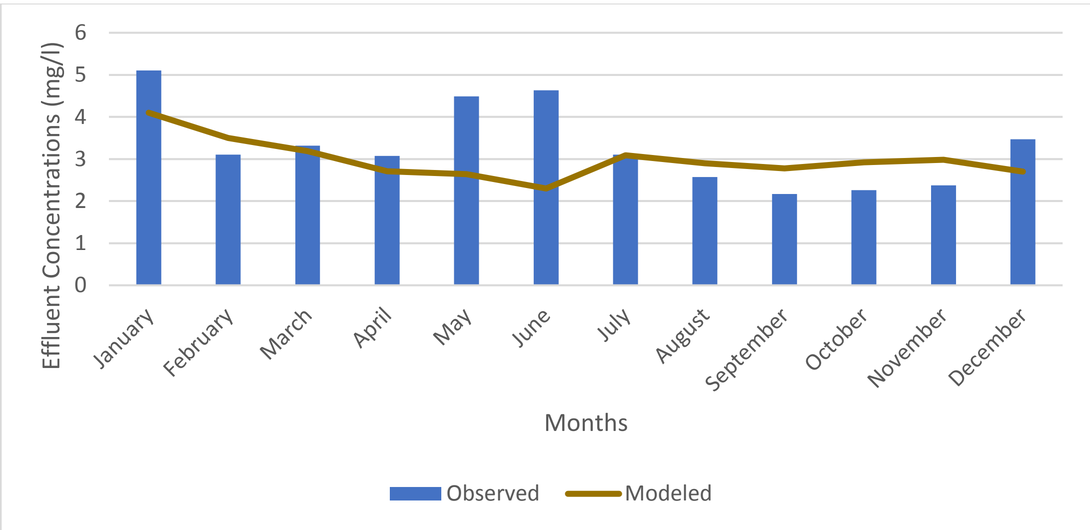

Figure 5-12 Effluent TN concentrations for 2017 Validation

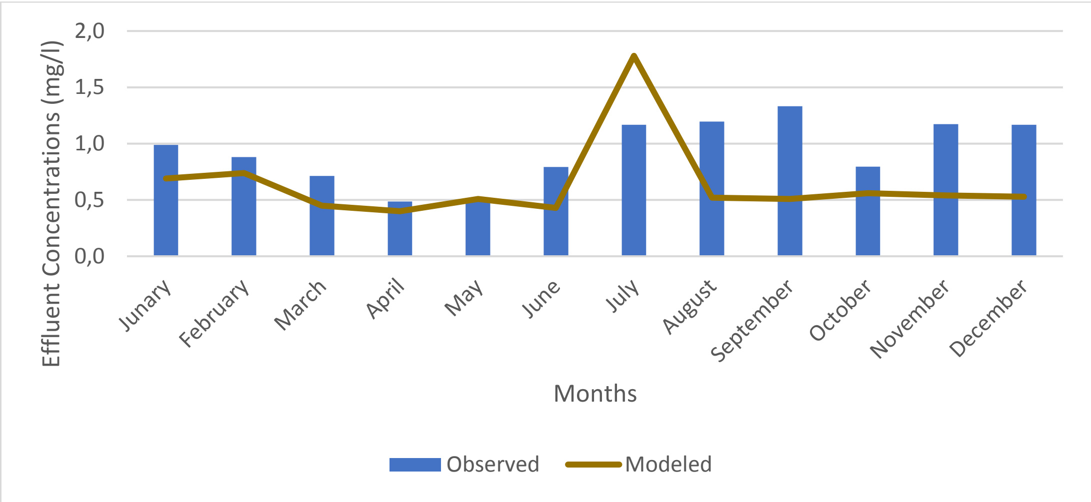

Figure 5-13 Effluent TP concentrations for 2017 Validation

It was observed that the calibrated model still overestimated TSS and COD concentrations and underestimates BOD concentration. Yet the values were observed to be in the same trend. In order not to disrupt TN and TP effluent concentrations, it was decided that there is no need for further calibration as they were less than 5%. Removal efficiency errors of validation are provided in Table 5-9.

Table 5-9 Removal efficiency errors of validation results

Effluent Parameter	% error of Removal Efficiency
COD	1.14
BOD	1.02
TSS	0.79
TN	1.72
TP	4.86

It was observed that the targeted model accuracy for removal efficiency of effluent parameters was achieved. The removal efficiencies of the effluent parameters are under 5%. The most dramatic difference between the model and the real case is happening in the MLSS values. That is because steady-state simulation was applied. The MLSS value cannot be defined in BioWin. If it could be defined, the model effluents would be more accurate. A solution to this problem is dynamic modeling with daily data. However, the dynamic model could not be created because there were not enough daily log data available. With dynamic modeling and daily inflow data, further calibration could have been reached.

<u>Energy Consumption Validation</u>

The energy consumption data were available for the first eight months of 2017. Therefore, validation was performed for eight monthly data. Energy consumption validation is provided in Figure 5-14.

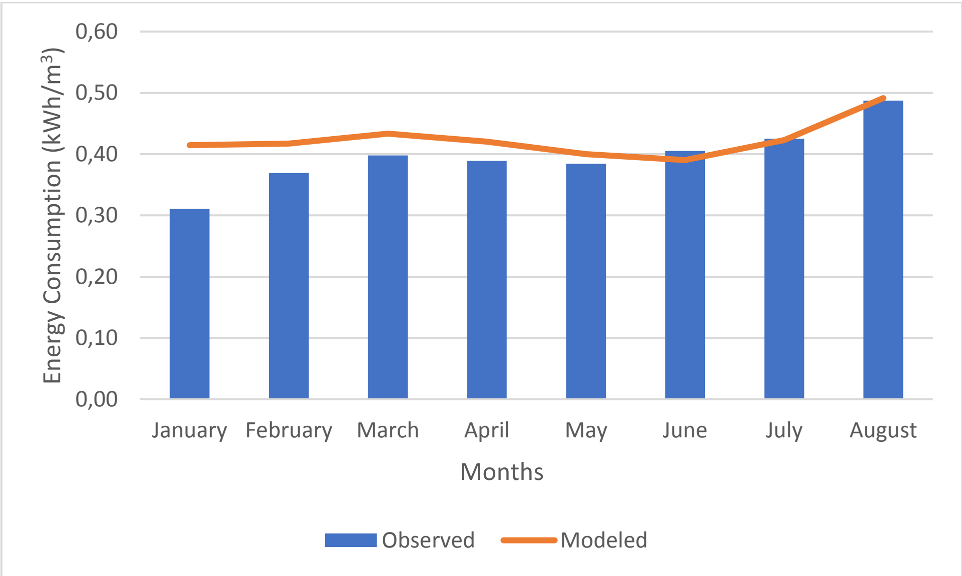

Figure 5-14 Energy Consumption for 2017 Validation

Modeled energy consumption values were observed to be in the same trend of real data. It was also observed that the targeted model accuracy (10%) for energy consumption was achieved. The average error of the energy consumption validation was calculated as 8.05%. Therefore, it was decided that there is no need for further calibration for energy calculation of the facility.

5.4.4. Management Scenarios

The purpose of simulating management scenarios using the calibrated model is to optimize the plant in terms of energy consumption and carbon footprint. Potential improvement methods were proposed and simulated. Management scenarios were divided into three categories; named as operational, structural and configurational changes in the system.

In operational change scenarios, internal recycle ratio, waste activated sludge flow, return activated sludge flow and re-aeration airflow were modified. All these operational parameters were varied to the extent that the discharge criteria are not violated.

In structural change scenarios, the idea was to carry out a construction activity through a component addition or replacing an existing component. For this matter, the structural changes can be described as; adding primary sedimentation, replacing the belt filter thickening unit with a gravity thickener, replacing the decanter dewatering unit with a belt press. Moreover, instead of lime stabilization, use of anaerobic digestion stabilization was considered. However, since there is a complete combustion plant operating next to the plant, lowering the calorific value of the sludge may make this idea infeasible.

Configuration change scenarios were simulated with the motivation provided by the flexibility of the existing system for such variations. To illustrate, component cancellation or reordering of bioreactors is possible. The scenarios can be described as; removing the sludge buffer tank, changing Bardenpho5 configuration to A2O configuration and reducing the number of the secondary clarifiers.

All of the four oxidation ditches in a single-line are connected with canals and gates. In the guidebook of the facility (Personal Communications, 2019), a description of the gate valve usage to change the configuration from Bardenpho to A2O is presented. In this A2O configuration, the last oxidation ditch tank (OD4) is located between the aeration oxidation ditches (OD1 & OD3), and the tank is getting the same aeration as

OD1 and OD3. This lineup creates constant aeration in three oxidation ditches following one unaerated oxidation ditch. The A2O process flow direction between the tanks (arrows) and wastewater inlet and outlet points (bold arrows) are provided in Figure 5-15. The oxidation ditch line up presented in BioWin software environment is depicted in Figure 5-16.

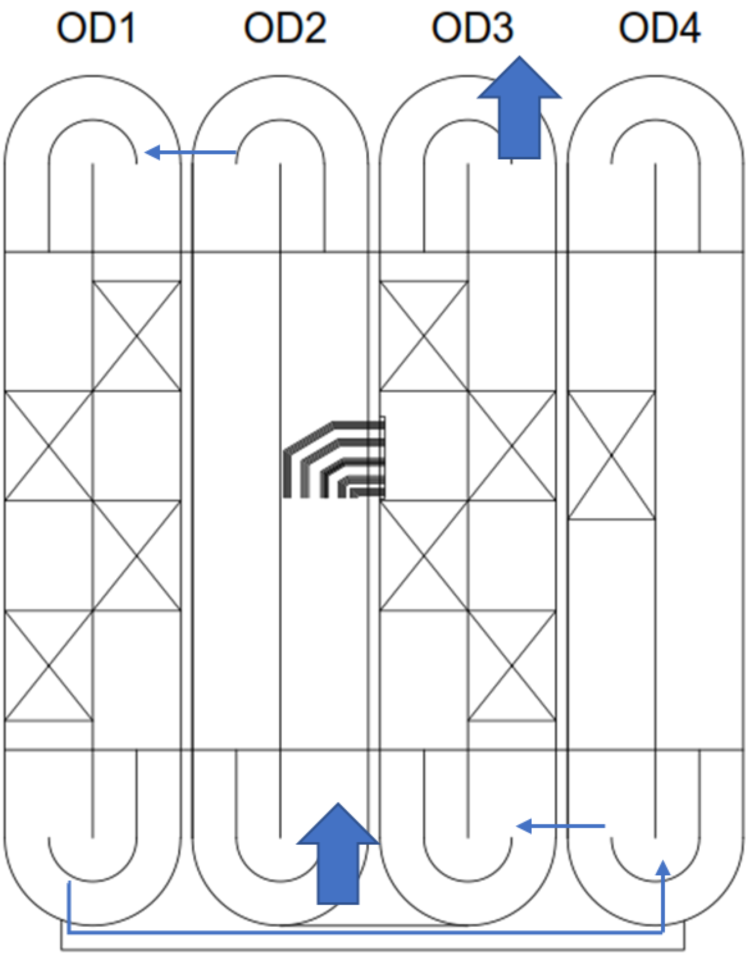

Figure 5-15 A2O process flow direction

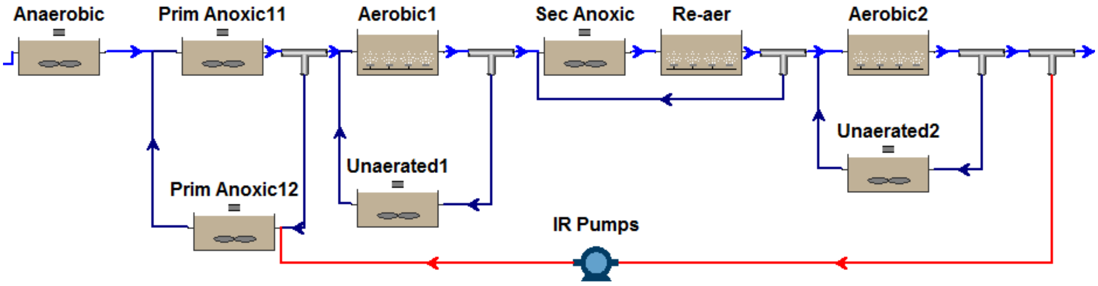

Figure 5-16 A2O configuration line up of Bursa East Municipal WWTP

In the normal line up (*Figure 5-4*), OD4 re-aeration zone is aerated for only N_2 stripping at a lower aeration rate, which is not enough to achieve the set DO as 1.5 mg/l. With A2O configuration, the airflow rate of OD4 should increase in order to keep a continuous aeration zone between OD1, OD4 and OD3. Without any simulation, it can be intuitively estimated that energy consumption is expected to increase in A2O configuration. Therefore, a new proposal was made as given below to alter the configuration for reducing energy consumption.

Since OD4 diffusers' placement area, which has an only re-aeration purpose, is smaller than placement area of aeration tanks diffusers (OD1 & OD3) (Figure 5-7), instead of providing continuous aeration in OD4, the tank can be operated in anoxic conditions without any aeration. This new scenario makes the configuration as anaerobic, anoxic(OD2), aerobic(OD1), anoxic(OD4), aerobic(OD3) in series (Bardenpho-5) (Figure 5-15). However, in this configuration, internal recycle (IR) is diverted to the last aerobic tank (OD3 to OD2) which is different from Bardenpho5 process. Therefore, this scenario was named as Modified Bardenpho-5.

The effects of optimization scenarios are given in Table 5-10. Except for the primary sedimentation addition scenario, all scenarios are applicable in terms of complying with the effluent standards. However, when primary sedimentation is added to the system, the system MLSS value drops dramatically and TN effluent spikes to 35 mg/l.

Table 5-10 Energy Consumption and Carbon footprint of the Scenarios

No.	Scenarios	Energy Consumption Kw/h	Carbon Footprint $kgCO_2eq$ /h	Energy Consumption Change (%)	Carbon Footprint Change (%)
0	Base Model	5,203.9	9,659.0	-	-
1.1	IR Reduction	4,952.7	10,112.1	-4.8	4.7
1.2	WAS Reduction	5,161.8	7,974.8	-0.8	-17.4
1.3	RAS Reduction	5,071.4	9,709.7	-2.5	0.5
1.4	Re-Aeration DO Reduction	5,134.2	9,801.9	-1.3	1.5
2.1	Primary sedimentation	-	-	-	-
2.2	Gravity Thickener	4,634.5	9,351.9	-10.9	-3.2
2.3	Belt Filter Dewatering	5,248.8	9,690.5	0.9	0.3
3.1	A2O Configuration	5,474.9	6,107.3	5.2	-15.4
3.2	Modified Bardenpho-5	5,082.5	7,832.6	-2.3	-18.9
3.3	Sludge Buffer Cancelation	5,200.9	9,655.7	-0.1	0.0

Gravity thickener replacement with belt filter thickener seems to be a good option. However, there is a risk of phosphorous release from sludge to the system in the real case since the sludge buffer tank is getting little aeration to prevent phosphorous release. Sludge buffer tank canceling option has no significant effect on the system since the tank has separate blowers with small capacity. If there is a risk in P release to the system, it is better to keep that unit working. A2O and Modified Bardenpho-5 configurations lower the carbon footprint considerably. Moreover, decreasing sludge unit’s flowrate also has a significant effect on energy consumption and carbon footprint.

To achieve optimal results, both energy and carbon footprint reductions were taken into consideration to select the best possible scenario approach. Characteristics of the best approach for Bursa East Municipal WWTP can be proposed as;

- Modified Bardenpho-5 Process
- 300% internal recycle
- 6000 m^3/day waste activated sludge flowrate
- 200000 m^3/day return activated sludge flowrate

Energy and carbon footprint results of the optimal approach are given in Table 5-11.

Table 5-11 Energy Consumption and Carbon Footprint Results of Optimal Management Model

Energy Consumption kW/h	Carbon Footprint $kgCO_2eq$ /h	Energy Consumption Change (%)	Carbon Footprint Change (%)
4,729.67	6,403.45	-9.11	-11.33

In 2017, the facility has paid nearly 14M TL for energy expenses. This number should increase to 18M TL for 2019 with the increase in the unit value of the 1 kWh electricity. Some of the scenarios stated in Table 5-10, have a significant impact with no investment value such as; IR, RAS and WAS optimization and Modified Bardenpho-5 configuration. With final optimization, the facility may save up to 1.6 M TL annually.

The facility has 3,477 metric tons of CO_2eq/year carbon footprint, which is equivalent to 443,360,331 smartphones charged or 1,478,909 liters of gasoline consumed (USEPA, 2011). These equivalence values were calculated by using US EPA's carbon footprint converter in order to understand the proposed carbon footprint reduction.

5.5. Conclusion

In this study, Bursa East WWTP operation was simulated to examine its energy consumption and carbon footprint. Impacts of various management options on energy usage and carbon footprint were evaluated.

Three variables were tested for a better simulation approach, which are having two different air-flow input, having two different WW fractions and OD simulation approach. The results revealed that for better calibration the model should be based on set DO value, default wastewater fractions should be used and oxidation ditch tanks should be assumed to be not fully aerated. As sensitivity analysis conducted for 57 selected parameters revealed, calibration could be improved for one raw wastewater fraction parameter and a settling parameter. It was possible to achieve successful calibration and validation of the model.

Energy consumption and carbon footprint analyses were done after the model validation was completed. Moreover, energy consumption was also calibrated and validated. It was simulated that the system was consuming 5,203.92 kWh with the 2017 annual average inputs. In the real case, annual daily average consumption was stated as 5,242.22 kWh for 2017 (Personal Communications, 2019). Additionally, as simulated, the system has a 9,659 kgCO_2eq/h GHG emissions. However, there was no real data for GHG emissions for comparison. With model optimization, both energy consumption and carbon footprint were reduced by 10% of their annual averages (modeled).

The biggest advantage of Bursa East Municipal WWTP in terms of carbon footprint is having a combustion facility near the treatment plant, which effortlessly eliminates the cost and carbon footprint that would have emerged from transporting the sludge.

It can be seen that the facility can be optimizable in terms of energy consumption and carbon footprint. Therefore, it can be deduced that a modeling study could provide better and more sustainable solutions for an existing WWTP.

CHAPTER 6

CONCLUSIONS AND FUTURE RECOMMENDATIONS

6.1. Highlights and Conclusions

In this thesis study, information on municipal WWTPs of Turkey was analyzed to determine the traditional technologies concerning biological treatment and sludge stabilization of municipal wastewaters. Combinations of different units and processes were used to build a set of WWTP models. These models were then used to determine relevant sludge production amounts, energy consumptions, carbon footprints and net present values. Bursa East Domestic WWTP was then employed for the simulation-based optimization of a real WWTP.

The problem of wastewater treatment system identification is a difficult task without a modeling study in the design stage. In addition, operating these facilities efficiently is another problem since these plants consumes tremendous amount of energy and produce significant amount of GHGs.

6.1.1. Hypothetical Models (Chapter 3 &4)

Turkey's most used wastewater treatment technologies are conventional AS, extended aeration, A/O, A2O and Bardenpho-5. Turkey's most used sludge treatment methods are aerobic and anaerobic sludge stabilization. As well as these processes, only thickening and dewatering were considered in the models as well. 105 hypothetical treatment combinations were prepared to represent Turkey's domestic WWTPs.

Among these models, it was observed that models with extended aeration wastewater treatment had the lowest sludge outputs, however, extended aeration process consumed more energy and produced more GHG than other treatment options due to its high aeration volume. On the other hand, conventional AS and A/O processes were observed to have the lowest energy consumptions among other treatment options. However, these treatment options have a downside of having high waste sludge outputs.

It was deducted that low SRT, using diffusers for aeration and anaerobic digestion with struvite recovery could be solutions to minimize carbon footprint and energy consumption. This suggestion can be also well optimized with land application to prevent the waste activated sludge resulting in GHG emissions due to combustion.

A2O and Bardenpho-5 processes can be operated with or without primary sedimentation and anaerobic stabilization. Another finding of these BNR processes is that Bardenpho-5 process is more suitable than A2O systems for wastewaters that have a high TKN/COD ratio. Lastly, it was also observed that there is no significant energy consumption or carbon footprint difference among the BNR technologies considered.

It can be stated that carbon footprint influencers are changing with respect to different wastewater strengths. The N_2O emissions were observed to contribute up to 50% of the total carbon footprint for HS wastewaters, while this value drops down to 8% of the total carbon footprint for LS wastewaters. On the other hand, the GHG emissions arising from electrical consumption and sludge transportation contribute 42% and 40% of the total carbon footprint for LS wastewaters. A2O and Bardenpho-5 processes have the lowest carbon footprints for high strength wastewaters. This indicates that nitrogen removal should be strongly suggested for high strength wastewaters to reduce carbon footprint of a WWTP.

6.1.2. Real Case Study (Chapter 5)

Bursa East WWTP was modeled, calibrated and validated to perform a modeling study in order to lower energy consumption and the carbon footprint of the facility. It was observed that both energy consumption and carbon footprint could be reduced by 9% and 11% of their annual averages, respectively. This corresponds to 520 kWh and 960 $kgCO_2eq/h$ reduction in energy consumption and GHG emission, respectively.

A modeling study is strongly suggested for wastewater facilities to investigate the impacts of various management options on energy usage and carbon footprint and analyze the impact of operational changes, as well as treatment process, changes on the performance of a WWTP. Especially for modifications that have a cost to implement cannot be done on a trial-and-error basis.

6.1.3. Comparison of Hypothetical and Real Case Models

When the Bursa East Municipal WWTP was classified under the scheme combinations discussed in Chapters 3 & 4, the facility should be classified under S_ BD5_001 code because of having Bardenpho-5 process followed by thickening and dewatering units as sludge treatment processes. Moreover, the influent wastewater characteristics of the system are between the HS and MS wastewater. Therefore, the facility's attributes should be between HS_BD5_001 and MS_BD5_001 hypothetical models.

SEC1 values of HS_ BD5_001 and MS_BD5_001 were calculated as 0.34 and 0.58 kWh/m^3, respectively. SEC1 value of Bursa East Municipal WWTP was calculated as 0.51 kWh/m^3 which is between the theoretical model values. Moreover, SEC2 values of HS_ BD5_001 and MS_BD5_001 were calculated 0.87 and 1.35 kWh/(mg/L COD_r). SEC2 value of Bursa East Municipal WWTP was calculated as 1.25 kWh/(mg/L COD_r). This might indicate that hypothetical models can provide a guide and be validated with real case studies. Considering the comparison, it can be deduced that adequate inputs were provided for calculating energy consumption of hypothetical cases. On the other hand, if we divide the hourly carbon footprint values to the selected flow rate, it was calculated that HS_ BD5_001 and MS_BD5_001 have a relative hourly carbon footprint of 32.39 $kgCO_2eq$ and 20.91 $kgCO_2eq$ for 1m^3 of wastewater treatment. This flow relative carbon footprint value was calculated as 21.67 $kgCO_2eq$ for 1m^3 for Bursa East Municipal WWTP. Bursa East WWTP has a carbon footprint value in the lower boundary of carbon footprint level deducted from hypothetical models. The main reason for that result can be stated as Bursa East Municipal WWTP has a complete combustion facility near the treatment plant, which effortlessly eliminates the cost and carbon footprint that would have emerged from transporting the sludge.

6.2. Future Recommendations

This thesis study will hopefully enlighten energy consumption and carbon footprint assessment of existing and new domestic WWTPs of Turkey. It was observed that modeling study has major potential for understanding and inferencing the operations in a treatment plant.

The sludge production is inevitable for all WWTPs. The fate of the waste sludges should be assessed for every WWTPs in our country, although, an action plan for treatment of sludges is expected to be published for Turkey's WWTPs. It can be said that all the waste sludges that are not used for land application will eventually turn in to GHGs. Ministry of Agriculture and Forestry should regulate the use of waste sludges as fertilizer.

In this study, it was deducted that a WWTP without nitrogen removal can achieve energy production using anaerobic sludge processes. The system can be operated in low SRT conditions to maximize waste sludge output to be processed in anaerobic digestion. Moreover, without nutrient removal, waste sludge of the facility will be nutrient-rich. Therefore, the WWTP should be considered as a power plant and a fertilizer production plant.

It can be strongly suggested that a benchmark system should be created for Turkey's WWTPs. In this benchmark convention, removal efficiency, energy consumption and carbon footprint values could be used to create a rubric. As shown in this study, new treatment plants could propose their possible benchmark values to Ministry of Environment and Urbanization in the design stage. On the other hand, existing treatment plants could also test different investment or operational change options in a model environment and claim their improvement projects by proposing the rise of their benchmark values.

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APPENDICES

Appendix A. Created Model Design Parameter Tables

Table A-1 Conventional AS Prosses Models Design Parameters

Model Name	Design Parameters				
	Aerobic (m^3)	Total Reactor (m^3)	RAS (%)	SRT (days)	Sludge Stabilization Volume (m^3)
HS_CON_00_000	30000	30000	50	5	-
HS_CON_00_001	30000	30000	50	5	-
HS_CON_00_AED	30000	30000	50	5	8600
HS_CON_00_AND	30000	30000	50	5	5000
HS_CON_TH_AND	30000	30000	50	5	10000
MS_CON_00_000	12500	12500	50	5	-
MS_CON_00_001	12500	12500	50	5	-
MS_CON_00_AED	12500	12500	50	5	4500
MS_CON_00_AND	12500	12500	50	5	3000
MS_CON_TH_AND	12500	12500	50	5	6000
LS_CON_00_000	7500	7500	50	5	-
LS_CON_00_001	7500	7500	50	5	-
LS_CON_00_AED	7500	7500	50	5	3000
LS_CON_00_AND	7500	7500	50	5	1500
LS_CON_TH_AND	7500	7500	50	5	3000

Table A-2 Extended Aeration Prosses Model Design Parameters

Model Name	Design Parameters				
	Aerobic (m^3)	Total Reactor (m^3)	RAS (%)	SRT (days)	Sludge Stabilization Volume (m^3)
HS_EXT_00_000	200000	200000	50	30	-
HS_EXT_00_001	200000	200000	50	30	-
HS_EXT_00_AED	200000	200000	50	30	5000
HS_EXT_00_AND	200000	200000	50	30	3000
HS_EXT_TH_AND	200000	200000	50	30	6000
MS_EXT_00_000	150000	150000	50	30	-
MS_EXT_00_001	150000	150000	50	30	-
MS_EXT_00_AED	150000	150000	50	30	2500
MS_EXT_00_AND	150000	150000	50	30	1500
MS_EXT_TH_AND	150000	150000	50	30	3000
LS_EXT_00_000	75000	75000	50	30	-
LS_EXT_00_001	75000	75000	50	30	-
LS_EXT_00_AED	75000	75000	50	30	1250
LS_EXT_00_AND	75000	75000	50	30	750
LS_EXT_TH_AND	75000	75000	50	30	2000

Table A-3 A/O Phoredox Processes Model Design Parameters

Model Name	Design Parameters					
	Anaerobic (m^3)	Aerobic (m^3)	Total Reactor (m^3)	RAS (%)	SRT (days)	Sludge Stabilization Volume (m^3)
HS_AO_00_000	7500	15000	22500	50	5	-
HS_AO_00_001	7500	15000	22500	50	5	-
HS_AO_00_AED	7500	15000	22500	50	5	6000
HS_AO_00_AND	7500	15000	22500	50	5	5000
HS_AO_TH_AND	7500	15000	22500	50	5	8000
MS_AO_00_000	5000	10000	15000	50	5	-
MS_AO_00_001	5000	10000	15000	50	5	-
MS_AO_00_AED	5000	10000	15000	50	5	4500
MS_AO_00_AND	5000	10000	15000	50	5	3000
MS_AO_TH_AND	5000	10000	15000	50	5	5000
LS_AO_00_000	3500	5000	8500	50	5	-
LS_AO_00_001	3500	5000	8500	50	5	-
LS_AO_00_AED	3500	5000	8500	50	5	2500
LS_AO_00_AND	3500	5000	8500	50	5	1750
LS_AO_TH_AND	3500	5000	8500	50	5	3000

Table A-4 A2OS Processes Model Design Parameters

Model Name	Design Parameters							
	Anaerobic (m^3)	**Anoxic (m^3)**	**Aerobic (m^3)**	**Total Reactor (m^3)**	**IR (%)**	**RAS (%)**	**SRT (days)**	**Sludge Stabilization Volume (m^3)**
HS_A2OS_00_000	10000	20000	30000	60000	400	50	10	-
HS_A2OS_00_001	10000	20000	30000	60000	400	50	10	-
HS_A2OS_00_AED	10000	20000	30000	60000	400	50	10	8000
HS_A2OS_00_AND	10000	20000	30000	60000	400	50	10	5000
HS_A2OS_TH_AND	10000	20000	30000	60000	400	50	10	8000
MS_A2OS_00_000	7500	7500	15000	30000	400	50	10	-
MS_A2OS_00_001	7500	7500	15000	30000	400	50	10	-
MS_A2OS_00_AED	7500	7500	15000	30000	400	50	10	5000
MS_A2OS_00_AND	7500	7500	15000	30000	400	50	10	3000
MS_A2OS_TH_AND	7500	7500	15000	30000	400	50	10	5000
LS_A2OS_00_000	5000	5000	10000	20000	400	50	10	-
LS_A2OS_00_001	5000	5000	10000	20000	400	50	10	-
LS_A2OS_00_AED	5000	5000	10000	20000	400	50	10	2600
LS_A2OS_00_AND	5000	5000	10000	20000	400	50	10	1500
LS_A2OS_TH_AND	5000	5000	10000	20000	400	50	10	3000

Table A-5 Bardenpho-5S Processes Model Design Parameters

Model Name	Design Parameters									
	Anaerobic (m^3)	**Anoxic (m^3)**	**Aerobic (m^3)**	**Sec. Anox (m^3)**	**Re. Aer (m^3)**	**Total Reactor (m^3)**	**IR (%)**	**RAS (%)**	**SRT (days)**	**Sludge Stabilization Volume (m^3)**
HS_BD5S_00_000	10000	15000	20000	10000	2000	57000	400	100	15	-
HS_BD5S_00_001	10000	15000	20000	10000	2000	57000	400	100	15	-
HS_BD5S_00_AED	10000	15000	20000	10000	2000	57000	400	100	15	8000
HS_BD5S_00_AND	10000	15000	20000	10000	2000	57000	400	100	15	5000
HS_BD5S_TH_AND	10000	15000	20000	10000	2000	57000	400	100	15	8000
MS_BD5S_00_000	7500	10000	15000	7500	1500	41500	400	100	15	-
MS_BD5S_00_001	7500	10000	15000	7500	1500	41500	400	100	15	-
MS_BD5S_00_AED	7500	10000	15000	7500	1500	41500	400	100	15	4500
MS_BD5S_00_AND	7500	10000	15000	7500	1500	41500	400	100	15	3000
MS_BD5S_TH_AND	7500	10000	15000	7500	1500	41500	400	100	15	5000
LS_BD5S_00_000	5000	7500	10000	5000	1000	28500	400	100	15	-
LS_BD5S_00_001	5000	7500	10000	5000	1000	28500	400	100	15	-
LS_BD5S_00_AED	5000	7500	10000	5000	1000	28500	400	100	15	2500
LS_BD5S_00_AND	5000	7500	10000	5000	1000	28500	400	100	15	1500
LS_BD5S_TH_AND	5000	7500	10000	5000	1000	28500	400	100	15	3000

Table A-6 A2O Processes Model Design Parameters

Model Name	Design Parameters							
	Anaerobic (m^3)	Anoxic (m^3)	Aerobic (m^3)	Total Reactor (m^3)	IR (%)	RAS (%)	SRT (days)	Sludge Stabilization Volume (m^3)
HS_A2O_00_000	10000	20000	30000	60000	400	50	10	-
HS_A2O_00_001	10000	20000	30000	60000	400	50	10	-
HS_A2O_00_AED	10000	20000	30000	60000	400	50	10	8000
HS_A2O_00_AND	10000	20000	30000	60000	400	50	10	5000
HS_A2O_TH_AND	10000	20000	30000	60000	400	50	10	8000
MS_A2O_00_000	7500	7500	15000	30000	400	50	10	-
MS_A2O_00_001	7500	7500	15000	30000	400	50	10	-
MS_A2O_00_AED	7500	7500	15000	30000	400	50	10	5000
MS_A2O_00_AND	7500	7500	15000	30000	400	50	10	3000
MS_A2O_TH_AND	7500	7500	15000	30000	400	50	10	5000
LS_A2O_00_000	5000	5000	10000	20000	400	50	10	-
LS_A2O_00_001	5000	5000	10000	20000	400	50	10	-
LS_A2O_00_AED	5000	5000	10000	20000	400	50	10	2600
LS_A2O_00_AND	5000	5000	10000	20000	400	50	10	1500
LS_A2O_TH_AND	5000	5000	10000	20000	400	50	10	3000

Table A-7 Bardenpho-5 Processes Model Design Parameters

Model Name	Design Parameters									
	Anaerobic (m^3)	Anoxic (m^3)	Aerobic (m^3)	Sec. Anox (m^3)	Re. Aer (m^3)	Total Reactor (m^3)	IR (%)	RAS (%)	SRT (days)	Sludge Stabilization Volume (m^3)
HS_BD5_00_000	10000	15000	30000	10000	2000	67000	400	100	15	-
HS_BD5_00_001	10000	15000	30000	10000	2000	67000	400	100	15	-
HS_BD5_00_AED	10000	15000	30000	10000	2000	67000	400	100	15	8000
HS_BD5_00_AND	10000	15000	30000	10000	2000	67000	400	100	15	5000
HS_BD5_TH_AND	10000	15000	30000	10000	2000	67000	400	100	15	8000
MS_BD5_00_000	7500	10000	15000	7500	1500	41500	400	100	15	-
MS_BD5_00_001	7500	10000	15000	7500	1500	41500	400	100	15	-
MS_BD5_00_AED	7500	10000	15000	7500	1500	41500	400	100	15	4500
MS_BD5_00_AND	7500	10000	15000	7500	1500	41500	400	100	15	3000
MS_BD5_TH_AND	7500	10000	15000	7500	1500	41500	400	100	15	5000
LS_BD5_00_000	5000	7500	10000	5000	1000	28500	400	100	15	-
LS_BD5_00_001	5000	7500	10000	5000	1000	28500	400	100	15	-
LS_BD5_00_AED	5000	7500	10000	5000	1000	28500	400	100	15	2500
LS_BD5_00_AND	5000	7500	10000	5000	1000	28500	400	100	15	1500
LS_BD5_TH_AND	5000	7500	10000	5000	1000	28500	400	100	15	3000

Appendix B. BioWin Layout Figures

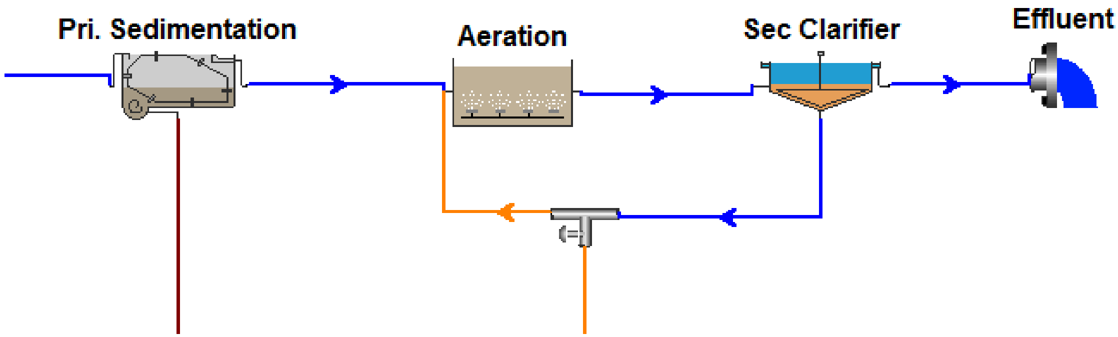

Figure B-1 BioWin Layout of Conventional AS Process

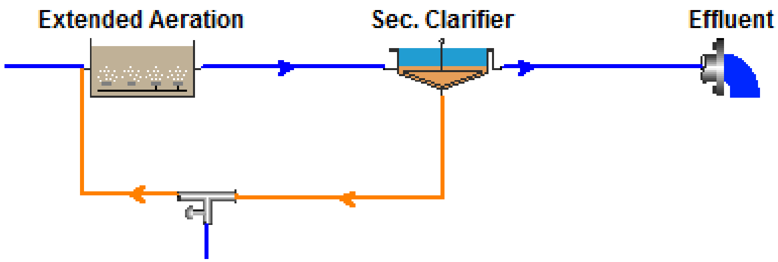

Figure B-2 BioWin Layout of Extended Aeration Process

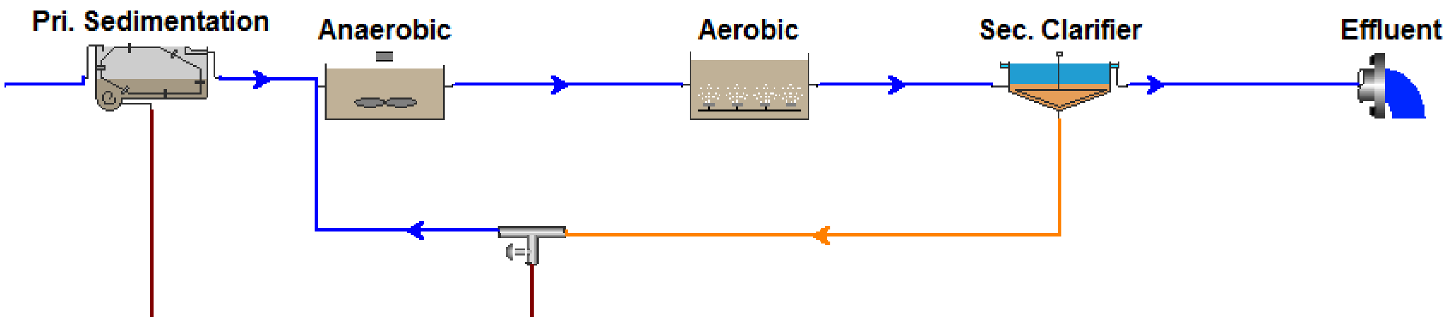

Figure B-3 BioWin Layout of A/O Process

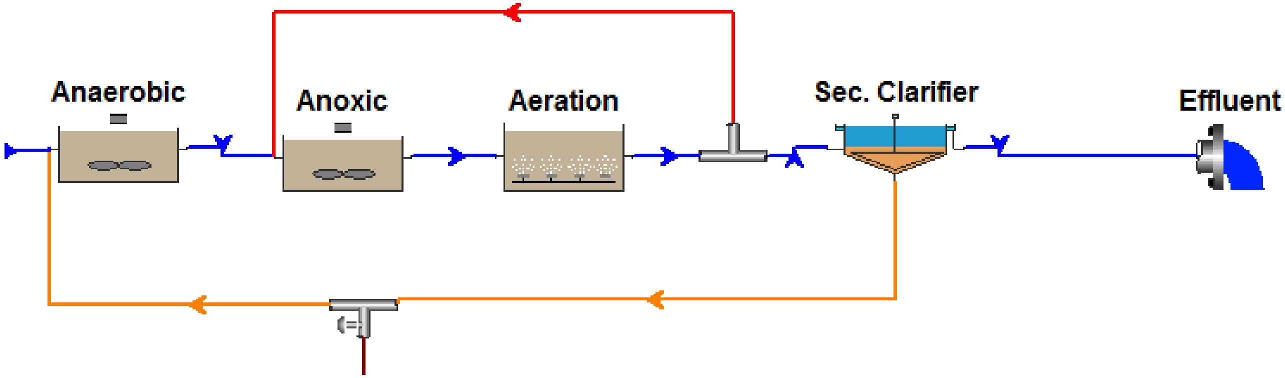

Figure B-4 BioWin Layout of A2O Process

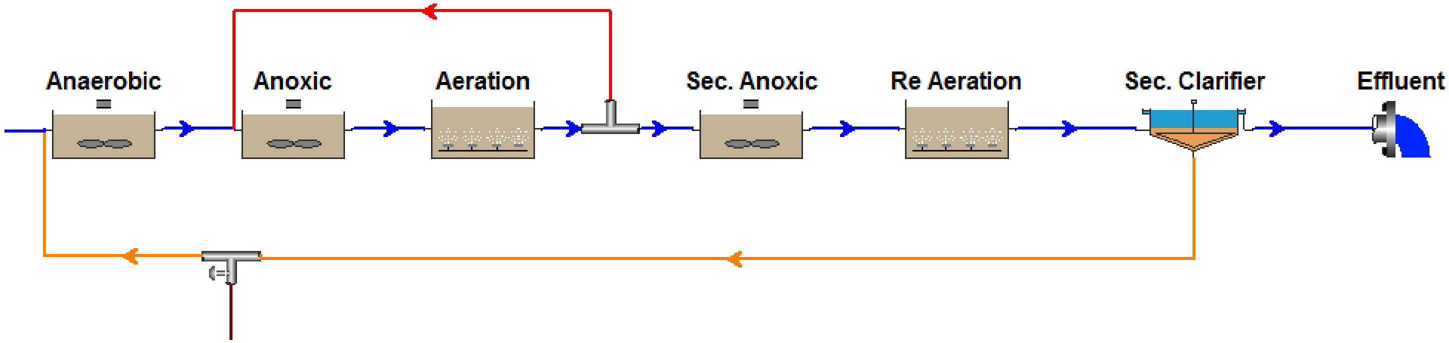

Figure B-5 BioWin Layout of Bardenpho-5 Process

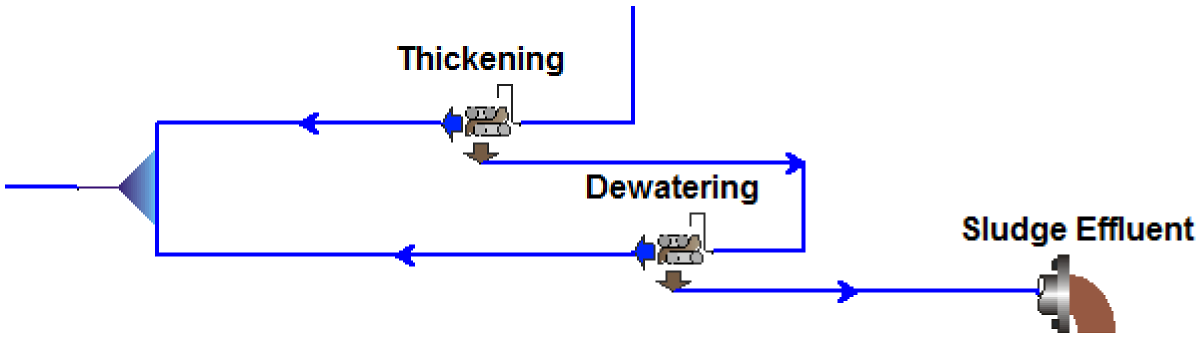

Figure B-6 BioWin Layout of Only Thickening and Dewatering Sludge Process

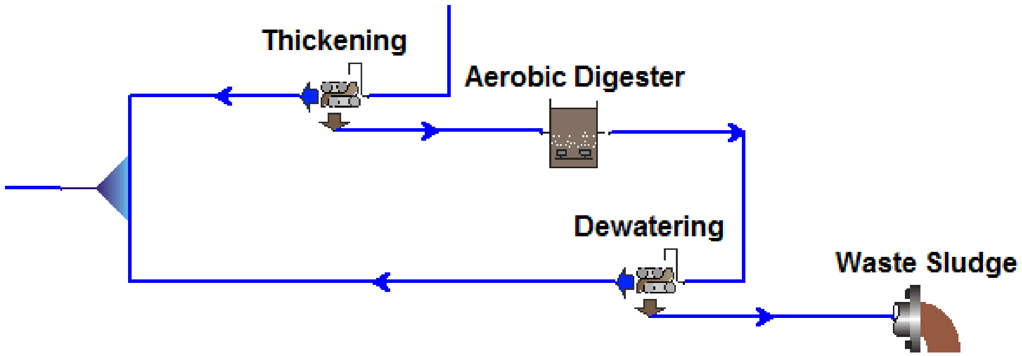

Figure B-7 BioWin Layout Of Aerobic Sludge Process

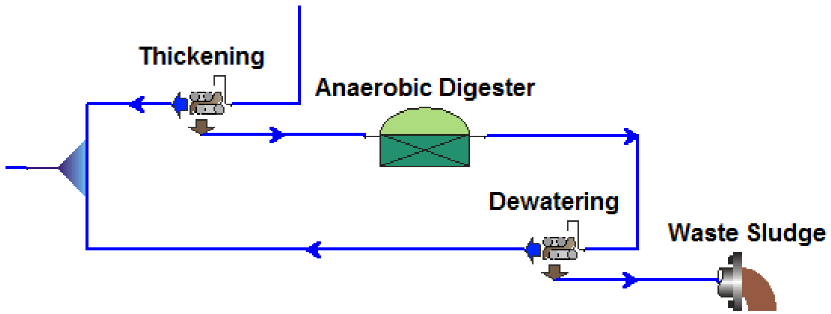

Figure B-8 BioWin Layout of Anaerobic Sludge Process

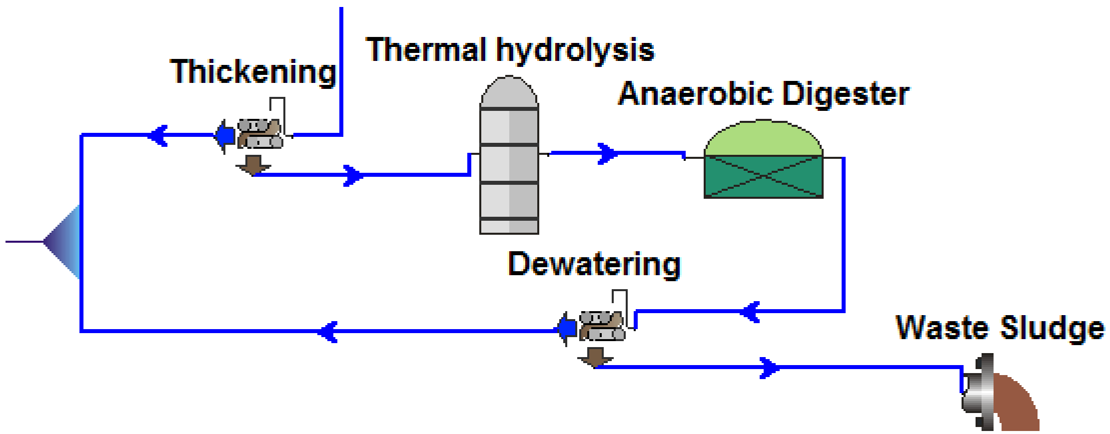

Figure B-9 BioWin Layout of Anaerobic Sludge Process with Thermal Hydrolysis

Appendix C. Model Effluent Charts

Table C-1 Conventional AS Processes Model Effluents

Model Name	EFFLUENT (mg/L)					Sludge	Stabilization			
	BOD	COD	TSS	TN	TP	TSS (kg/d)	% VSS Reduction	Biogas Production (m^3/h)	CH_4 (%)	Methene Production (m^3/h)
HS_CON_00_000	6.7	39.6	9.0	46.4	4.2	37328	-	-	-	-
HS_CON_00_001	6.9	40.3	9.7	46.5	4.3	36658	-	-	-	-
HS_CON_00_AED	6.9	40.3	9.6	50.9	6.9	21966	44.05	-	-	-
HS_CON_00_AND	6.9	40.4	9.7	54.0	7.5	18976	52.5	659.78	64.65	426.55
HS_CON_TH_AND	6.9	53.8	9.7	57.0	8.5	15041	63.75	814.44	59.7	486.22
MS_CON_00_000	7.7	40.8	10.7	27.8	2.9	19026	-	-	-	-
MS_CON_00_001	7.9	41.7	11.4	27.9	2.9	18645	-	-	-	-
MS_CON_00_AED	7.9	41.7	11.5	30.3	4.4	11045	44.52	-	-	-
MS_CON_00_AND	7.9	41.8	11.5	31.9	4.7	9423	53.9	352.17	64.73	227.96
MS_CON_TH_AND	7.8	48.4	10.8	33.4	5.2	9255	65.15	439.92	59.73	262.76
LS_CON_00_000	7.2	28.7	9.2	13.7	1.7	10614	-	-	-	-
LS_CON_00_001	7.3	29.4	9.9	13.7	1.8	10375	-	-	-	-
LS_CON_00_AED	7.3	29.4	9.9	14.7	2.6	5685	49.49	-	-	-
LS_CON_00_AND	7.4	29.4	9.9	15.8	2.8	4853	58.12	219.47	63.74	139.89
LS_CON_TH_AND	6.2	31.8	9.0	16.7	3.1	2865	68.36	253.47	58.74	148.89

Table C-2 Extended Aeration Processes Model Effluents

Model Name	EFFLUENT (mg/L)					Sludge	Stabilization			
	BOD	COD	TSS	TN	TP	TSS (kg/d)	% VSS Reduction	Biogas Production (m^3/h)	CH_4 (%)	Methene Production (m^3/h)
HS_EXT_00_000	3.1	37.7	9.0	52.6	7.7	19995	-	-	-	-
HS_EXT_00_001	3.1	38.7	9.8	53.0	7.9	19487	-	-	-	-
HS_EXT_00_AED	3.1	38.7	9.8	54.6	8.4	16977	14.38	-	-	-
HS_EXT_00_AND	3.1	38.7	9.9	54.5	8.4	17048	14.02	71.71	71.31	51.14
HS_EXT_TH_AND	3.1	40.7	9.9	55.5	8.7	15915	20.53	111.16	64.63	71.84
MS_EXT_00_000	2.5	33.2	6.2	31.1	4.8	10313	-	-	-	-
MS_EXT_00_001	2.5	33.9	6.8	31.3	4.9	10037	-	-	-	-
MS_EXT_00_AED	2.5	33.9	6.8	32.2	2.2	8737	14.45	-	-	-
MS_EXT_00_AND	2.5	33.9	6.8	32.1	5.1	8869	13.1	34.05	71.68	24.41
MS_EXT_TH_AND	2.5	34.8	6.7	32.5	5.3	8128	20.96	57.4	64.89	37.25
LS_EXT_00_000	2.7	23.1	6.4	15.1	2.8	5338	-	-	-	-
LS_EXT_00_001	2.7	23.8	7.0	15.3	2.9	5160	-	-	-	-
LS_EXT_00_AED	2.7	23.8	7.0	15.8	3.0	4401	16.63	-	-	-
LS_EXT_00_AND	2.7	23.8	7.0	15.8	3.0	4473	15.17	20.3	71.51	14.52
LS_EXT_TH_AND	2.7	24.3	7.0	16.0	3.1	4067	24.06	34.25	64.8	22.19

Table C-3 A/O Phoredox Processes Model Effluents

Model Name	EFFLUENT (mg/L)					Sludge	Stabilization			
	BOD	COD	TSS	TN	TP	TSS (kg/d)	% VSS Reduction	Biogas Production (m^3/h)	CH_4 (%)	Methene Production (m^3/h)
HS_AO_00_000	7.9	45.1	13.0	39.1	0.8	38709	-	-	-	-
HS_AO_00_001	8.2	46.2	13.9	38.0	0.9	38090	-	-	-	-
HS_AO_00_AED	8.0	47.2	14.8	37.5	0.8	24464	43.47	-	-	-
HS_AO_00_AND	8.1	47.4	15.8	44.4	1.0	21956	51.85	658.67	64.45	424.51
HS_AO_TH_AND	7.6	57.6	14.4	43.8	0.8	18716	64.93	827	60.46	500.00
MS_AO_00_000	6.5	39.3	9.9	23.0	0.8	20002	-	-	-	-
MS_AO_00_001	6.7	40.0	10.6	22.2	0.8	19668	-	-	-	-
MS_AO_00_AED	6.5	40.2	11.6	22.1	0.7	12677	44.36	-	-	-
MS_AO_00_AND	6.5	39.8	11.7	26.1	0.9	11443	52.39	356.64	64.33	229.43
MS_AO_TH_AND	6.7	47.0	12.3	27.0	0.8	9691	65.28	440.91	59.74	263.40
LS_AO_00_000	6.9	29.2	9.2	13.7	0.7	11212	-	-	-	-
LS_AO_00_001	7.1	29.9	9.9	13.7	0.7	10999	-	-	-	-
LS_AO_00_AED	7.0	30.2	10.2	13.6	1.0	6682	45.99	-	-	-
LS_AO_00_AND	6.9	29.6	11.1	15.8	0.9	5832	56.29	223.44	63.39	141.64
LS_AO_TH_AND	7.0	34.6	12.2	16.9	0.9	4601	70.87	280.86	58.03	162.98

Table C-4 A2O with Primary Sedimentation Processes Model Effluents

Model Name	EFFLUENT (mg/L)					Sludge	Stabilization			
	BOD	COD	TSS	TN	TP	TSS (kg/d)	% VSS Reduction	Biogas Production (m^3/h)	CH_4 (%)	Methene Production (m^3/h)
HS_A2OS_00_000	5.9	43.6	11.4	14.9	1.1	36305	-	-	-	-
HS_A2OS_00_001	6.0	44.2	12.0	14.4	1.2	35347	-	-	-	-
HS_A2OS_00_AED	5.9	44.8	12.9	14.5	1.2	24132	39.49	-	-	-
HS_A2OS_00_AND	6.0	44.3	11.9	15.6	1.4	16579	48.93	481.23	76.85	369.83
HS_A2OS_TH_AND	6.0	55.9	11.9	16.8	1.5	14558	62.55	662.58	66.64	441.54
MS_A2OS_00_000	4.9	37.6	8.6	13.9	1.0	18767	-	-	-	-
MS_A2OS_00_001	5.0	36.1	9.5	13.4	0.8	18614	-	-	-	-
MS_A2OS_00_AED	4.9	38.3	10.3	13.8	1.0	12097	43.86	-	-	-
MS_A2OS_00_AND	5.0	38.4	9.2	15.1	1.3	8489	51.98	266.99	78.17	208.71
MS_A2OS_TH_AND	5.0	44.4	9.2	15.7	1.3	7627	62.99	347.9	68.12	236.99
LS_A2OS_00_000	4.5	25.1	6.9	7.4	0.8	10573	-	-	-	-
LS_A2OS_00_001	4.6	25.6	7.4	7.1	0.8	10339	-	-	-	-
LS_A2OS_00_AED	4.5	25.9	8.3	7.2	0.7	6592	46.09	-	-	-
LS_A2OS_00_AND	4.4	25.5	6.2	10.0	0.7	4687	54.6	164.2	78.79	129.37
LS_A2OS_TH_AND	4.4	29.3	6.2	10.3	0.7	4102	68.45	222.21	68.02	151.15

Table C-5 Bardenpho-5 with Primary Sedimentation Processes Model Effluents

Model Name	EFFLUENT (mg/L)					Sludge	Stabilization			
	BOD	COD	TSS	TN	TP	TSS (kg/d)	% VSS Reduction	Biogas Production (m^3/h)	CH_4 (%)	Methene Production (m^3/h)
HS_BD5S_00_000	7.1	50.2	16.2	9.6	1.0	34575	-	-	-	-
HS_BD5S_00_001	7.3	51.6	17.3	9.1	1.1	33853	-	-	-	-
HS_BD5S_00_AED	7.4	50.4	19.1	7.9	1.1	23029	42.46	-	-	-
HS_BD5S_00_AND	7.3	52.0	17.2	9.5	1.1	16074	50.13	473.74	76.43	362.08
HS_BD5S_TH_AND	7.3	62.4	17.2	10.3	1.1	14545	61.55	651.49	63.92	416.43
MS_BD5S_00_000	5.3	40.7	11.4	7.7	0.9	17990	-	-	-	-
MS_BD5S_00_001	5.5	41.5	12.2	7.3	1.0	17574	-	-	-	-
MS_BD5S_00_AED	5.4	41.7	13.5	7.4	0.9	11835	42.72	-	-	-
MS_BD5S_00_AND	5.4	41.7	12.1	8.1	1.1	8186	51.82	275.31	71.93	198.03
MS_BD5S_TH_AND	5.3	46.9	12.2	8.5	0.8	7554	61.92	345.17	64.04	221.05
LS_BD5S_00_000	4.7	27.5	8.6	5.4	0.9	10038	-	-	-	-
LS_BD5S_00_001	4.8	28.2	9.2	5.2	0.9	9800	-	-	-	-
LS_BD5S_00_AED	4.8	28.5	10.2	5.2	0.9	6245	46.08	-	-	-
LS_BD5S_00_AND	4.8	28.3	9.1	5.4	0.9	4288	56.28	167.95	73.71	123.80
LS_BD5S_TH_AND	4.8	31.8	9.1	5.6	1.0	3830	67.68	214.37	65.04	139.43

Table C-6 A2O Processes Model Effluents

Model Name	EFFLUENT (mg/L)					Sludge	Stabilization			
	BOD	COD	TSS	TN	TP	TSS (kg/d)	% VSS Reduction	Biogas Production (m^3/h)	CH_4 (%)	Methene Production (m^3/h)
HS_A2O_00_000	6.1	45.3	13.1	13.1	1.5	27999	-	-	-	-
HS_A2O_00_001	8.6	54.3	20.3	13.5	1.8	27037	-	-	-	-
HS_A2O_00_AED	8.5	54.4	21.5	13.6	1.1	21752	27.3	-	-	-
HS_A2O_00_AND	8.5	54.8	20.2	14.1	1.9	16729	24.95	128.58	94.95	122.09
HS_A2O_TH_AND	8.7	59.4	20.1	14.8	2.0	14694	42.97	239.82	82.13	196.96
MS_A2O_00_000	6.8	44.8	14.4	11.0	1.2	14443	-	-	-	-
MS_A2O_00_001	7.0	43.9	16.0	11.3	0.9	14285	-	-	-	-
MS_A2O_00_AED	6.9	46.0	16.6	11.7	1.5	10596	31.88	-	-	-
MS_A2O_00_AND	6.9	46.3	15.5	12.5	1.6	8362	29.82	87.13	87.62	76.34
MS_A2O_TH_AND	6.9	48.6	15.5	13.1	1.7	7570	43.67	120.52	89.57	107.95
LS_A2O_00_000	6.3	31.1	11.8	6.6	0.9	7833	-	-	-	-
LS_A2O_00_001	6.5	32.1	12.7	6.3	1.0	7527	-	-	-	-
LS_A2O_00_AED	3.4	32.1	13.5	6.3	1.0	5566	34.3	-	-	-
LS_A2O_00_AND	6.1	31.0	10.8	8.7	0.8	4747	30.87	49.67	91.91	45.65
LS_A2O_TH_AND	6.1	32.5	10.8	9.0	0.8	4173	49.74	79.03	89.97	71.10

Table C-7 Bardenpho-5 Processes Model Effluents

Model Name	EFFLUENT (mg/L)					Sludge	Stabilization			
	BOD	COD	TSS	TN	TP	TSS (kg/d)	% VSS Reduction	Biogas Production (m^3/h)	CH_4 (%)	Methene Production (m^3/h)
HS_BD5_00_000	6.5	50.5	17.8	8.0	0.8	26265	-	-	-	-
HS_BD5_00_001	6.7	52.0	19.4	7.7	0.9	25639	-	-	-	-
HS_BD5_00_AED	6.6	52.4	20.0	8.6	1.0	20786	25.14	-	-	-
HS_BD5_00_AND	6.6	52.4	19.3	8.7	0.9	16025	23.01	106.9	94.63	101.16
HS_BD5_TH_AND	6.6	55.8	19.3	9.7	0.9	14557	36.73	176.28	88.49	155.99
MS_BD5_00_000	6.1	45.9	14.8	5.9	1.1	13477	-	-	-	-
MS_BD5_00_001	7.8	52.4	21.1	6.0	1.0	12948	-	-	-	-
MS_BD5_00_AED	6.1	47.0	16.9	5.6	1.1	10540	27.56	-	-	-
MS_BD5_00_AND	8.2	55.1	21.4	6.1	1.0	8483	25.89	23.9	99.05	23.67
MS_BD5_TH_AND	6.0	48.3	16.0	5.8	0.8	7610	38.55	102.85	83.61	85.99
LS_BD5_00_000	5.7	31.5	11.7	5.0	1.0	7339	-	-	-	-
LS_BD5_00_001	5.8	32.4	12.5	4.6	1.0	7056	-	-	-	-
LS_BD5_00_AED	5.7	32.6	13.3	4.7	1.0	5452	30.66	-	-	-
LS_BD5_00_AND	5.8	32.7	12.5	4.7	1.1	4369	27.44	38.93	88.88	34.60
LS_BD5_TH_AND	5.7	33.8	12.4	4.8	1.1	3938	43.9	61.39	87.81	53.91

Appendix D. Model Result Tables

Table D-1 Conventional AS Prosses Models Results

Model Name	Total Management Cost (TL/h)	SEC1 (kwh/m^3)	SEC2 (kwh/ mg/l COD$_r$)	Management cost for WW (MTL/m^3)	Capital Cost (MTL)	Net Present Value 20 years (MTL)	NVP W/o Capital Cost (MTL)	NPV for WW (m^3)	Green Hause Gas Emmision (kgCO2e/h)
HS_CON_00_000	3,516.92	0.48	0.63	0.84	9.16	572.73	583.02	0.80	4,765.46
HS_CON_00_001	1,421.98	0.58	0.77	0.34	12.19	240.06	235.73	0.33	4,945.08
HS_CON_00_AED	1,592.78	0.77	1.01	0.38	15.92	271.16	264.04	0.38	4,433.34
HS_CON_00_AND	722.07	0.29	0.38	0.17	45.61	161.32	119.70	0.22	4,672.91
HS_CON_TH_AND	842.58	0.25	0.33	0.20	77.57	212.59	139.68	0.30	4,539.38
MS_CON_00_000	1,625.89	0.28	0.72	0.39	9.04	269.59	269.53	0.37	1,801.09
MS_CON_00_001	747.59	0.33	0.84	0.18	10.02	129.82	123.93	0.18	1,878.06
MS_CON_00_AED	866.80	0.43	1.09	0.21	12.05	150.95	143.69	0.21	1,673.14
MS_CON_00_AND	435.57	0.18	0.47	0.10	29.06	98.86	72.21	0.14	1,527.70
MS_CON_TH_AND	510.01	0.16	0.42	0.12	48.23	129.96	84.55	0.18	1,454.54
LS_CON_00_000	978.51	0.16	0.74	0.23	9.74	166.55	162.21	0.23	1,048.16
LS_CON_00_001	437.63	0.19	0.87	0.11	10.44	80.56	72.55	0.11	1,061.89
LS_CON_00_AED	506.06	0.25	1.14	0.12	14.28	95.38	83.89	0.13	931.12
LS_CON_00_AND	223.92	0.10	0.46	0.05	20.97	56.85	37.12	0.08	798.48
LS_CON_TH_AND	252.29	0.10	0.45	0.06	31.17	71.60	41.82	0.10	723.25

Table D-2 Extended Aeration Prosses Models Results

Model Name	Total Management Cost (TL/h)	SEC1 (kwh/m^3)	SEC2 (kwh/ mg/l COD$_r$)	Management cost for WW (MTL/m^3)	Capital Cost (MTL)	Net Present Value 20 years (MTL)	NVP W/o Capital Cost (MTL)	NPV for WW (m^3)	Green Hause Gas Emmision (kgCO2e/h)
HS_EXT_00_000	3,560.65	0.77	1.02	0.85	19.66	590.24	590.27	0.82	5,538.48
HS_EXT_00_001	1,686.39	0.86	1.13	0.40	21.26	291.50	279.56	0.40	5,696.74
HS_EXT_00_AED	1,709.08	0.89	1.17	0.41	23.17	297.04	283.32	0.41	5,620.12
HS_EXT_00_AND	1,600.53	0.82	1.08	0.38	32.88	289.36	265.33	0.40	5,642.64
HS_EXT_TH_AND	1,671.24	0.81	1.06	0.40	51.44	319.25	277.05	0.44	5,623.74
MS_EXT_00_000	2,414.85	0.45	1.14	0.58	16.71	403.68	400.32	0.56	1,668.93
MS_EXT_00_001	966.19	0.51	1.28	0.23	17.70	172.53	160.17	0.24	1,780.75
MS_EXT_00_AED	992.58	0.52	1.32	0.24	18.26	177.32	164.55	0.25	1,742.25
MS_EXT_00_AND	952.22	0.49	1.25	0.23	23.60	176.19	157.85	0.24	1,729.68
MS_EXT_TH_AND	971.57	0.49	1.23	0.23	32.98	188.67	161.06	0.26	1,692.93
LS_EXT_00_000	1,276.20	0.27	1.19	0.31	14.33	218.84	211.56	0.30	947.08
LS_EXT_00_001	560.70	0.30	1.32	0.13	14.94	104.79	92.95	0.15	1,001.29
LS_EXT_00_AED	573.50	0.31	1.36	0.14	16.34	108.24	95.07	0.15	978.85
LS_EXT_00_AND	548.39	0.29	1.28	0.13	17.99	105.86	90.91	0.15	969.42
LS_EXT_TH_AND	575.95	0.29	1.26	0.14	25.02	117.32	95.48	0.16	951.15

Table D-3 A/O Phoredox Prosses Models Results

Model Name	Total Management Cost (TL/h)	SEC1 (kwh/m^3)	SEC2 (kwh/ mg/l COD_r)	Management cost for WW (MTL/m^3)	Capital Cost (MTL)	Net Present Value 20 years (MTL)	NVP W/o Capital Cost (MTL)	NPV for WW (m^3)	Green Hause Gas Emmision (kgCO2e/h)
HS_AO_00_000	2,563.05	0.25	0.33	0.62	12.79	423.51	424.89	0.59	3,669.53
HS_AO_00_001	926.46	0.34	0.45	0.22	14.24	162.70	153.58	0.23	4,025.73
HS_AO_00_AED	1,271.70	0.52	0.70	0.31	20.20	223.99	210.82	0.31	3,705.85
HS_AO_00_AND	564.13	0.05	0.06	0.14	48.00	138.40	93.52	0.19	3,224.84
HS_AO_TH_AND	671.00	0.05	0.07	0.16	71.40	178.93	111.24	0.25	4,192.05
MS_AO_00_000	1,582.11	0.16	0.40	0.38	8.86	262.38	262.27	0.36	1,880.58
MS_AO_00_001	545.13	0.21	0.54	0.13	11.60	98.96	90.37	0.14	2,082.74
MS_AO_00_AED	744.01	0.31	0.79	0.18	14.15	133.38	123.34	0.19	1,905.97
MS_AO_00_AND	349.27	0.05	0.12	0.08	30.65	86.62	57.90	0.12	1,662.58
MS_AO_TH_AND	553.72	0.04	0.11	0.13	45.15	133.88	91.79	0.19	1,743.88
LS_AO_00_000	920.99	0.09	0.40	0.22	6.31	153.90	152.68	0.21	864.21
LS_AO_00_001	352.32	0.12	0.54	0.08	7.05	63.51	58.41	0.09	920.02
LS_AO_00_AED	361.15	0.17	0.79	0.09	9.10	66.97	59.87	0.09	802.11
LS_AO_00_AND	147.59	0.02	0.07	0.04	18.47	42.12	24.47	0.06	648.28
LS_AO_TH_AND	238.30	0.00	0.01	0.06	27.37	65.56	39.50	0.09	587.64

Table D-4 A2O with Primary Sedimentation Prosses Models Results

Model Name	Total Management Cost (TL/h)	SEC1 (kwh/m^3)	SEC2 (kwh/ mg/l COD$_r$)	Management cost for WW (MTL/m^3)	Capital Cost (MTL)	Net Present Value 20 years (MTL)	NVP W/o Capital Cost (MTL)	NPV for WW (m^3)	Green Hause Gas Emmision (kgCO2e/h)
HS_A2OS_00_000	4,151.64	0.36	0.47	1.00	18.90	684.19	688.24	0.95	5,059.06
HS_A2OS_00_001	1,209.86	0.49	0.64	0.29	21.28	215.16	200.56	0.30	5,091.64
HS_A2OS_00_AED	1,323.17	0.64	0.84	0.32	27.24	239.28	219.35	0.33	4,722.19
HS_A2OS_00_AND	584.48	0.23	0.31	0.14	52.45	146.11	96.89	0.20	4,268.16
HS_A2OS_TH_AND	675.87	0.18	0.25	0.16	75.56	183.86	112.04	0.26	4,487.91
MS_A2OS_00_000	1,670.71	0.21	0.55	0.40	14.30	282.03	276.96	0.39	2,913.91
MS_A2OS_00_001	653.29	0.27	0.68	0.16	15.36	120.05	108.30	0.17	2,896.54
MS_A2OS_00_AED	837.93	0.35	0.90	0.20	18.01	152.28	138.91	0.21	2,717.39
MS_A2OS_00_AND	297.35	0.12	0.31	0.07	33.56	81.21	49.29	0.11	2,459.51
MS_A2OS_TH_AND	360.93	0.10	0.27	0.09	47.82	105.66	59.83	0.15	2,483.28
LS_A2OS_00_000	1,107.30	0.15	0.65	0.27	10.26	187.71	183.56	0.26	1,187.83
LS_A2OS_00_001	408.82	0.18	0.80	0.10	11.07	76.58	67.77	0.11	1,247.04
LS_A2OS_00_AED	451.53	0.23	1.02	0.11	13.06	85.42	74.85	0.12	1,148.69
LS_A2OS_00_AND	206.32	0.09	0.39	0.05	20.51	53.57	34.20	0.07	778.56
LS_A2OS_TH_AND	224.61	0.07	0.32	0.05	30.86	66.85	37.23	0.09	748.54

Table D-5 Bardenpho-5 with Primary Sedimentation Prosses Models Results

Model Name	Total Management Cost (TL/h)	SEC1 (kwh/m^3)	SEC2 (kwh/ mg/l COD_r)	Management cost for WW (MTL/m^3)	Capital Cost (MTL)	Net Present Value 20 years (MTL)	NVP W/o Capital Cost (MTL)	NPV for WW (m^3)	Green Hause Gas Emmision (kgCO2e/h)
HS_BD5S_00_000	3,096.33	0.36	0.48	0.74	18.59	514.77	513.29	0.71	5,687.60
HS_BD5S_00_001	1,127.49	0.46	0.61	0.27	20.48	201.16	186.91	0.28	5,775.16
HS_BD5S_00_AED	1,575.83	0.62	0.82	0.38	26.15	278.67	261.23	0.39	3,808.76
HS_BD5S_00_AND	517.55	0.21	0.27	0.12	51.29	134.23	85.80	0.19	5,200.58
HS_BD5S_TH_AND	638.06	0.17	0.23	0.15	73.83	176.08	105.77	0.24	5,530.45
MS_BD5S_00_000	2,103.88	0.24	0.63	0.50	15.51	352.65	348.77	0.49	2,888.67
MS_BD5S_00_001	714.56	0.31	0.79	0.17	16.81	131.32	118.46	0.18	2,960.62
MS_BD5S_00_AED	910.45	0.38	0.99	0.22	19.23	165.12	150.93	0.23	2,805.08
MS_BD5S_00_AND	394.44	0.17	0.43	0.09	34.44	97.65	65.39	0.14	2,687.85
MS_BD5S_TH_AND	488.96	0.15	0.40	0.12	48.50	126.86	81.06	0.18	2,622.06
LS_BD5S_00_000	1,406.06	0.17	0.77	0.34	11.18	236.50	233.09	0.33	1,124.33
LS_BD5S_00_001	450.14	0.21	0.95	0.11	12.01	84.14	74.62	0.12	1,204.35
LS_BD5S_00_AED	554.57	0.26	1.17	0.13	14.03	102.89	91.93	0.14	1,113.58
LS_BD5S_00_AND	256.38	0.12	0.56	0.06	21.86	62.95	42.50	0.09	948.94
LS_BD5S_TH_AND	380.89	0.11	0.52	0.09	31.36	92.39	63.14	0.13	945.59

Table D-6 A2O Processes without Primary Sedimentation Models Results

Model Name	Total Management Cost (TL/h)	SEC1 (kwh/m^3)	SEC2 (kwh/ mg/l COD_r)	Management cost for WW (MTL/m^3)	Capital Cost (MTL)	Net Present Value 20 years (MTL)	NVP W/o Capital Cost (MTL)	NPV for WW (m^3)	Green Hause Gas Emmision (kgCO2e/h)
HS_A2O_00_000	4,065.80	0.46	0.61	0.98	18.04	669.57	674.01	0.93	3,388.13
HS_A2O_00_001	1,268.05	0.57	0.76	0.30	20.12	223.32	210.21	0.31	3,750.57
HS_A2O_00_AED	1,306.24	0.65	0.87	0.31	26.00	235.32	216.54	0.33	3,563.41
HS_A2O_00_AND	1,038.78	0.49	0.65	0.25	41.32	207.78	172.20	0.29	3,180.48
HS_A2O_TH_AND	1,089.21	0.29	0.39	0.26	64.87	239.41	180.56	0.33	2,746.58
MS_A2O_00_000	1,483.55	0.26	0.68	0.36	13.44	251.17	245.94	0.35	2,284.48
MS_A2O_00_001	711.00	0.31	0.80	0.17	14.48	128.41	117.87	0.18	2,184.31
MS_A2O_00_AED	819.73	0.35	0.92	0.20	16.98	148.34	135.89	0.21	2,112.64
MS_A2O_00_AND	534.49	0.26	0.67	0.13	27.25	112.90	88.61	0.16	1,967.71
MS_A2O_TH_AND	576.53	0.24	0.63	0.14	41.66	134.04	95.57	0.19	1,929.09
LS_A2O_00_000	974.38	0.17	0.79	0.23	9.40	165.54	161.53	0.23	973.64
LS_A2O_00_001	419.80	0.20	0.92	0.10	10.09	77.36	69.59	0.11	1,023.15
LS_A2O_00_AED	433.75	0.23	1.04	0.10	12.07	81.58	71.90	0.11	966.48
LS_A2O_00_AND	334.25	0.17	0.77	0.08	16.29	69.85	55.41	0.10	828.42
LS_A2O_TH_AND	356.65	0.15	0.69	0.09	26.67	83.83	59.12	0.12	806.48

Table D-7 Bardenpho-5 Processes without Primary Sedimentation Models Results

Model Name	Total Management Cost (TL/h)	SEC1 (kwh/m^3)	SEC2 (kwh/ mg/l COD_r)	Management cost for WW (MTL/m^3)	Capital Cost (MTL)	Net Present Value 20 years (MTL)	NVP W/o Capital Cost (MTL)	NPV for WW (m^3)	Green Hause Gas Emmision (kgCO2e/h)
HS_BD5_00_000	3,286.99	0.49	0.65	0.79	18.76	545.49	544.90	0.76	3,436.57
HS_BD5_00_001	1,480.09	0.58	0.77	0.36	20.54	257.72	245.36	0.36	3,239.27
HS_BD5_00_AED	1,586.43	0.64	0.85	0.38	26.20	280.42	262.99	0.39	3,097.10
HS_BD5_00_AND	1,245.47	0.51	0.68	0.30	40.84	240.42	206.47	0.33	2,728.05
HS_BD5_TH_AND	1,177.30	0.36	0.49	0.28	63.41	252.07	195.17	0.35	2,403.69
MS_BD5_00_000	1,900.00	0.29	0.76	0.46	14.65	319.12	314.97	0.44	2,038.41
MS_BD5_00_001	789.47	0.34	0.91	0.19	15.78	142.29	130.87	0.20	2,091.72
MS_BD5_00_AED	888.84	0.38	0.99	0.21	18.19	160.62	147.35	0.22	2,008.17
MS_BD5_00_AND	693.67	0.33	0.88	0.17	26.42	137.57	114.99	0.19	1,813.63
MS_BD5_TH_AND	771.39	0.29	0.76	0.19	42.06	165.67	127.88	0.23	1,826.08
LS_BD5_00_000	1,277.02	0.20	0.92	0.31	10.32	214.96	211.70	0.30	995.74
LS_BD5_00_001	468.49	0.24	1.08	0.11	11.05	86.12	77.66	0.12	1,063.36
LS_BD5_00_AED	540.83	0.26	1.18	0.13	13.06	99.72	89.66	0.14	1,018.04
LS_BD5_00_AND	401.99	0.21	0.97	0.10	17.32	81.74	66.64	0.11	927.42
LS_BD5_TH_AND	556.65	0.22	1.04	0.13	26.96	116.16	92.28	0.16	971.97

Appendix E. GHG Emissions

Table E-1 Conventional AS Prosses Model GHG Emissions

Model Name	**Electrical Consuption**	**Sludge Transportation**	**N_2O Emissions**	**CH_4 Emissions**	**CO2 Emissions**	**Total GVP**
	kgCO2e/hr	**kgCO2e/hr**	**kgCO2e/hr**	**kgCO2e/hr**	**kgCO2e/hr**	**kgCO2e/hr**
HS_CON_00_000	1079.64	2177.48	1451.69	0.00	56.65	4765.46
HS_CON_00_001	1314.25	2138.38	1434.13	0.00	58.33	4945.08
HS_CON_00_AED	1728.07	1281.35	1336.29	0.00	87.63	4433.34
HS_CON_00_AND	644.63	1106.93	2066.31	30.63	824.41	4672.91
HS_CON_TH_AND	559.54	877.39	2148.26	19.38	934.81	4539.38
MS_CON_00_000	633.11	1109.85	26.83	0.00	31.30	1801.09
MS_CON_00_001	736.35	1087.63	21.95	0.00	32.14	1878.06
MS_CON_00_AED	956.50	644.29	24.59	0.00	47.76	1673.14
MS_CON_00_AND	414.10	549.68	17.07	14.84	532.01	1527.70
MS_CON_TH_AND	361.05	539.85	36.58	10.55	506.50	1454.54
LS_CON_00_000	366.98	619.15	45.37	0.00	16.67	1048.16
LS_CON_00_001	430.72	605.21	8.78	0.00	17.18	1061.89
LS_CON_00_AED	563.76	331.63	8.78	0.00	26.95	931.12
LS_CON_00_AND	226.93	283.09	10.24	9.14	269.07	798.48
LS_CON_TH_AND	219.76	208.09	4.39	4.22	286.80	723.25

Table E-2 Extended Aeration Prosses Model GHG Emissions

Model Name	Electrical Consuption	Sludge Transportation	N_2O Emissions	CH_4 Emissions	CO2 Emissions	Total GVP
	kgCO2e/hr	kgCO2e/hr	kgCO2e/hr	kgCO2e/hr	kgCO2e/hr	kgCO2e/hr
HS_EXT_00_000	1743.23	1166.38	2536.55	0.00	92.33	5538.48
HS_EXT_00_001	1930.45	1136.74	2536.55	0.00	93.00	5696.74
HS_EXT_00_AED	1995.98	990.33	2536.55	0.00	97.26	5620.12
HS_EXT_00_AND	1844.81	994.47	2614.60	4.17	184.60	5642.64
HS_EXT_TH_AND	1815.25	928.38	2653.62	4.17	222.33	5623.74
MS_EXT_00_000	1015.03	601.59	0.00	0.00	52.31	1668.93
MS_EXT_00_001	1142.51	585.49	0.00	0.00	52.75	1780.75
MS_EXT_00_AED	1178.12	509.66	0.00	0.00	54.47	1742.25
MS_EXT_00_AND	1112.42	517.36	0.00	3.13	96.77	1729.68
MS_EXT_TH_AND	1095.54	474.13	0.00	3.13	120.14	1692.93
LS_EXT_00_000	605.66	311.38	0.00	0.00	30.03	947.08
LS_EXT_00_001	670.01	301.00	0.00	0.00	30.28	1001.29
LS_EXT_00_AED	690.73	256.73	0.00	0.00	31.39	978.85
LS_EXT_00_AND	652.00	260.93	0.00	0.00	56.50	969.42
LS_EXT_TH_AND	641.90	237.24	0.00	1.56	70.45	951.15

Table E-3 A/O Phoredox Processes Model GHG Emissions

Model Name	Electrical Consuption	Sludge Transportation	N_2O Emissions	CH_4 Emissions	CO2 Emissions	Total GVP
	kgCO2e/hr	kgCO2e/hr	kgCO2e/hr	kgCO2e/hr	kgCO2e/hr	kgCO2e/hr
HS_AO_00_000	568.03	2258.03	806.33	2.89	34.26	3669.53
HS_AO_00_001	758.20	2221.92	1005.35	3.05	37.21	4025.73
HS_AO_00_AED	1177.39	1427.07	1041.06	2.73	57.59	3705.85
HS_AO_00_AND	108.31	1280.77	1131.20	32.81	671.75	3224.84
HS_AO_TH_AND	115.56	1091.77	2007.78	29.53	947.42	4192.05
MS_AO_00_000	353.38	1166.78	330.73	11.72	17.97	1880.58
MS_AO_00_001	478.04	1147.30	436.09	1.30	20.01	2082.74
MS_AO_00_AED	694.97	739.48	435.02	1.20	35.31	1905.97
MS_AO_00_AND	107.57	667.53	439.99	17.19	430.30	1662.58
MS_AO_TH_AND	92.17	565.31	576.58	13.75	496.07	1743.88
LS_AO_00_000	199.74	654.03	3.90	1.03	5.51	864.21
LS_AO_00_001	265.51	641.61	5.85	1.08	5.98	920.02
LS_AO_00_AED	390.75	389.78	5.85	1.03	14.69	802.11
LS_AO_00_AND	33.83	340.21	4.88	10.02	259.34	648.28
LS_AO_TH_AND	5.02	268.38	7.80	7.57	298.87	587.64

Table E-4 A2OS Processes Model GHG Emissions

Model Name	Electrical Consuption	Sludge Transportation	N_2O Emissions	CH_4 Emissions	CO2 Emissions	Total GVP
	kgCO2e/hr	**kgCO2e/hr**	**kgCO2e/hr**	**kgCO2e/hr**	**kgCO2e/hr**	**kgCO2e/hr**
HS_A2OS_00_000	800.24	2117.79	2097.53	1.35	42.15	5059.06
HS_A2OS_00_001	1095.36	2061.92	1888.75	1.67	43.95	5091.64
HS_A2OS_00_AED	1434.66	1407.68	1810.31	1.35	68.19	4722.19
HS_A2OS_00_AND	527.53	967.11	2031.19	37.40	704.93	4268.16
HS_A2OS_TH_AND	415.59	849.23	2360.94	25.00	837.15	4487.91
MS_A2OS_00_000	483.07	1094.73	1312.66	1.02	22.43	2913.91
MS_A2OS_00_001	599.26	1085.81	1186.81	1.17	23.49	2896.54
MS_A2OS_00_AED	793.79	705.67	1179.01	1.02	37.91	2717.39
MS_A2OS_00_AND	274.58	495.17	1279.01	14.69	396.07	2459.51
MS_A2OS_TH_AND	232.68	444.90	1346.32	10.78	448.60	2483.28
LS_A2OS_00_000	328.74	616.76	231.22	0.57	10.55	1187.83
LS_A2OS_00_001	402.94	603.11	229.26	0.68	11.05	1247.04
LS_A2OS_00_AED	516.57	384.53	227.31	0.68	19.59	1148.69
LS_A2OS_00_AND	198.05	273.42	57.56	10.99	238.55	778.56
LS_A2OS_TH_AND	157.72	239.28	65.36	7.45	278.73	748.54

Table E-5 Bardenpho-5S Processes Model GHG Emissions

Model Name	Electrical Consuption	Sludge Transportation	N_2O Emissions	CH_4 Emissions	CO2 Emissions	Total GVP
	kgCO2e/hr	**kgCO2e/hr**	**kgCO2e/hr**	**kgCO2e/hr**	**kgCO2e/hr**	**kgCO2e/hr**
HS_BD5S_00_000	817.24	2016.88	2810.30	1.67	41.52	5687.60
HS_BD5S_00_001	1029.28	1974.76	2726.59	1.67	42.86	5775.16
HS_BD5S_00_AED	1387.31	1343.36	1003.50	4.68	69.91	3808.76
HS_BD5S_00_AND	462.35	937.65	3082.10	28.93	689.55	5200.58
HS_BD5S_TH_AND	381.29	848.44	3468.44	21.98	810.30	5530.45
MS_BD5S_00_000	549.21	1049.39	1267.01	0.75	22.31	2888.67
MS_BD5S_00_001	688.96	1025.15	1222.52	0.92	23.07	2960.62
MS_BD5S_00_AED	862.76	690.37	1214.91	0.75	36.29	2805.08
MS_BD5S_00_AND	375.58	477.53	1435.98	13.48	385.28	2687.85
MS_BD5S_TH_AND	348.05	440.64	1402.91	10.16	420.30	2622.06
LS_BD5S_00_000	384.96	585.55	143.02	0.60	10.20	1124.33
LS_BD5S_00_001	474.01	571.67	147.31	0.71	10.65	1204.35
LS_BD5S_00_AED	582.27	364.31	147.71	0.60	18.69	1113.58
LS_BD5S_00_AND	278.54	250.13	180.09	8.77	231.41	948.94
LS_BD5S_TH_AND	255.73	223.39	199.80	5.77	260.90	945.59

Table E-6 A2O Processes Model GHG Emissions

Model Name	Electrical Consuption	Sludge Transportation	N_2O Emissions	CH_4 Emissions	CO2 Emissions	Total GVP
	kgCO2e/hr	kgCO2e/hr	kgCO2e/hr	kgCO2e/hr	kgCO2e/hr	kgCO2e/hr
HS_A2O_00_000	1041.06	1633.26	657.55	3.54	52.73	3388.13
HS_A2O_00_001	1278.20	1577.18	829.26	5.21	60.73	3750.57
HS_A2O_00_AED	1451.28	1268.87	766.43	4.79	72.05	3563.41
HS_A2O_00_AND	1095.53	975.84	809.74	21.25	278.13	3180.48
HS_A2O_TH_AND	647.55	857.17	798.04	18.23	425.59	2746.58
MS_A2O_00_000	589.30	842.50	819.50	2.81	30.37	2284.48
MS_A2O_00_001	697.35	833.30	619.02	2.58	32.07	2184.31
MS_A2O_00_AED	792.86	618.10	660.48	2.42	38.79	2112.64
MS_A2O_00_AND	581.75	487.81	721.45	8.52	168.18	1967.71
MS_A2O_TH_AND	537.04	441.57	718.53	7.97	223.99	1929.09
LS_A2O_00_000	390.59	456.95	108.29	2.24	15.57	973.64
LS_A2O_00_001	453.51	439.09	112.19	2.14	16.21	1023.15
LS_A2O_00_AED	507.71	324.68	112.19	2.03	19.86	966.48
LS_A2O_00_AND	378.32	276.89	68.29	10.10	94.81	828.42
LS_A2O_TH_AND	339.84	243.40	74.15	8.96	140.13	806.48

Table E-7 Bardenpho-5 Processes Model GHG Emissions

Model Name	Electrical Consuption	Sludge Transportation	N_2O Emissions	CH_4 Emissions	CO2 Emissions	Total GVP
	kgCO2e/hr	kgCO2e/hr	kgCO2e/hr	kgCO2e/hr	kgCO2e/hr	kgCO2e/hr
HS_BD5_00_000	1096.72	1532.13	740.48	3.28	63.97	3436.57
HS_BD5_00_001	1297.53	1495.63	377.36	3.30	65.45	3239.27
HS_BD5_00_AED	1429.14	1212.49	376.58	2.97	75.92	3097.10
HS_BD5_00_AND	1144.38	934.80	385.56	17.65	245.66	2728.05
HS_BD5_TH_AND	818.94	849.18	388.29	3.25	344.03	2403.69
MS_BD5_00_000	656.44	786.17	562.14	3.06	30.60	2038.41
MS_BD5_00_001	775.50	755.31	526.53	3.06	31.32	2091.72
MS_BD5_00_AED	853.17	614.85	500.48	2.71	36.96	2008.17
MS_BD5_00_AND	743.46	494.83	493.46	9.07	72.82	1813.63
MS_BD5_TH_AND	655.61	443.90	534.04	7.46	185.06	1826.08
LS_BD5_00_000	452.36	428.12	95.51	3.99	15.74	995.74
LS_BD5_00_001	529.65	411.59	102.14	3.73	16.24	1063.36
LS_BD5_00_AED	575.10	318.05	102.14	3.44	19.30	1018.04
LS_BD5_00_AND	474.98	254.87	113.07	6.67	77.83	927.42
LS_BD5_TH_AND	506.20	229.70	117.75	6.07	112.24	971.97

Appendix F. Bursa Sensitivity Analyses

Table F-1 Sensitivity Analyses Results of Fractional & Stoichiometric Parameters

No.	Fractional & Stoichiometric Parameters	Default Value	1% Chagenged Value (+ , -)	% Change of BOD Effluent	% Change of COD Effluent	% Change of TSS Effluent	% Change of TN Effluent	% Change of TP Effluent
1	FBS - readily biodegradable gCOD/Total COD	0.16	0.18	0.00	0.66	0.59	-14.73	2.73
			0.14	0.10	-0.68	-0.74	17.12	-2.80
2	FAC - Acetate gCOD/rbCOD	0.15	0.17	0.00	0.07	0.06	-1.48	0.28
			0.14	0.00	-0.07	-0.09	1.60	-0.35
3	fxsp - Non-colloidal Slowlybd gCOD/sdCOD	0.75	0.83	0.00	0.00	0.00	-0.11	0.00
			0.68	0.00	0.00	0.00	0.00	-0.07
4	Fus - Unbiodegradable soluble COD/total COD	0.05	0.06	-0.62	6.83	-0.42	2.51	1.40
			0.05	0.62	-6.82	0.39	-2.51	-1.40
5	Fup - Unbiodegradable particulate COD/total COD	0.13	0.14	-1.44	0.48	1.31	1.94	2.87
			0.12	1.44	-0.48	-1.31	-1.83	-2.66
6	FNA - Ammonia gNH3-N/gTKN	0.66	0.73	0.00	-0.04	-0.06	0.68	-0.35
			0.59	0.10	0.04	0.06	-0.80	0.35
7	Fnox - Particulate organic Nitrogen	0.5	0.55	0.00	0.01	0.03	-0.34	0.07
			0.45	0.00	-0.01	-0.03	0.34	-0.14
8	Fnus - Soluble Unbiodegradable TKN	0.02	0.02	0.00	0.03	0.03	-0.68	1.96
			0.02	0.00	-0.02	-0.03	0.57	-1.68

No.	Fractional & Stoichiometric Parameters	Default Value	1% Chagenged Value (+ , -)	% Change of BOD Effluent	% Change of COD Effluent	% Change of TSS Effluent	% Change of TN Effluent	% Change of TP Effluent
9	FupN - N:COD for Unbiodegradable part	0.035	0.04	0.10	0.08	0.09	-1.83	-0.84
			0.03	0.00	-0.07	-0.09	1.71	0.84
10	Fpo4 - Phospate gPO4-P/gTP	0.5	0.55	0.00	0.00	0.00	0.00	0.00
			0.45	0.00	0.00	0.00	0.00	0.00
11	FupP - P:COD for unbiodegradable part	0.011	0.01	0.00	0.00	-0.03	-2.74	0.00
			0.01	0.00	0.00	0.00	2.74	0.00
12	Fzbh - OHO COD fraction	0.02	0.02	0.10	0.01	0.06	-0.11	0.00
			0.02	0.00	-0.01	-0.06	0.11	-0.07
13	Biomass Volatile Fraction VSS/TSS	0.92	1.01	0.00	0.00	-0.80	0.00	0.00
			0.83	0.00	0.00	4.25	0.00	0.00
14	Endogeneous Volatile Fraction VSS/TSS	0.92	1.01	0.00	0.00	-0.45	0.00	0.00
			0.83	0.00	0.00	2.41	0.00	0.00
15	N in endegenous residue	0.07	0.08	0.10	0.08	0.09	-1.83	-1.19
			0.06	0.00	-0.08	-0.09	1.83	1.19
16	P in endegeneous Residue	0.022	0.02	0.00	0.00	-0.03	-3.31	0.00
			0.02	0.00	0.00	0.00	3.31	0.00
17	Endogeneous residue COD:VSS ratio	1.42	1.56	0.00	0.00	-1.31	0.00	0.00
			1.28	0.00	0.00	2.41	0.00	0.00
18	Particulate substarate COD: VSS	1.6	1.76	0.00	0.00	-0.06	0.00	0.00
			1.44	0.00	0.00	0.12	0.00	0.00
19	Particulate inert COD:VSS	1.6	1.76	0.00	0.00	-1.75	0.00	0.00
			1.44	0.00	0.00	3.24	0.00	0.00

No.	Fractional & Stoichiometric Parameters	Default Value	1% Chagenged Value (+ , -)	% Change of BOD Effluent	% Change of COD Effluent	% Change of TSS Effluent	% Change of TN Effluent	% Change of TP Effluent
20	No 19 and No 18 Combined	1.6	1.76	0.00	0.00	-1.81	0.00	0.00
			1.44	0.00	0.00	3.36	0.00	0.00
21	Temprature	21.4	23.54	-3.40	-0.35	-1.04	1.83	0.07
			19.26	3.91	0.47	1.19	-3.65	-0.21

Table F-2 Sensitivity Analyses Results of Kinetic Parameters

No.	Kinetic Parameters	Default Value	1% Chagenged Value (+ , -)	% Change of BOD Effluent	% Change of COD Effluent	% Change of TSS Effluent	% Change of TN Effluent	% Change of TP Effluent
1	Hydrolysis Rate (1/d)	2.1	2.31	-1.54	-0.07	0.00	-3.42	4.41
			1.89	2.16	0.17	0.00	2.74	-5.25
2	Hydrolysis Half Sat	0.06	0.07	0.93	0.07	0.00	0.68	-1.68
			0.05	-0.93	-0.07	-0.09	-0.68	1.89
3	Anoxic Hydrolysis factor	0.28	0.31	-0.31	0.22	0.27	-6.85	-1.26
			0.25	0.31	-0.24	-0.27	7.19	1.47
4	Anaerobic Hydrolysis Factor (AS)	0.04	0.04	0.00	0.04	0.00	-1.03	0.00
			0.04	0.00	-0.04	-0.09	1.03	-0.21
5	Anaerobic Hydrolysis Factor (AS)	0.5	0.55	0.00	0.00	0.00	0.00	0.00
			0.45	0.00	0.00	0.00	0.00	0.00
6	Adsorption rate of colloids	0.15	0.17	0.00	0.00	0.00	0.00	0.00
			0.14	0.00	0.00	0.00	0.00	0.00
7	Ammonification rate	0.08	0.09	0.00	-0.02	0.00	0.34	-0.63
			0.07	0.00	0.02	0.00	-0.34	0.63
8	Assimilative nitrate/nitrite reduction rate	0.5	0.55	0.00	0.00	-0.09	0.00	0.00
			0.45	0.00	0.00	-0.09	0.00	0.00
9	Max spec growth rate of AOBs	0.9	0.99	0.00	-0.02	-0.09	0.68	-0.84
			0.81	0.00	0.02	0.09	-1.03	0.63
10	Substrate (NH4) halfsaturation of of AOBs	0.7	0.77	0.00	0.02	0.00	-0.34	0.21

No.	Kinetic Parameters	Default Value	1% Chagenged Value (+ , -)	% Change of BOD Effluent	% Change of COD Effluent	% Change of TSS Effluent	% Change of TN Effluent	% Change of TP Effluent
			0.63	0.00	0.00	-0.09	0.34	-0.42
11	Aerobic Decay rate of AOBs	0.17	0.19	0.00	0.00	0.00	-0.34	0.21
			0.15	0.00	0.00	-0.09	0.34	-0.42
12	Anoxic/anaerobic decay rate of AOBs	0.08	0.09	0.00	0.00	0.00	-0.34	0.00
			0.07	0.00	0.00	0.00	0.00	-0.21
13	Max spec growth rate of NOBs	0.7	0.77	0.00	-0.02	-0.09	0.68	0.63
			0.63	0.00	0.07	0.09	-1.03	-1.05
14	Substrate (NO2) halfsat of NOBs	0.1	0.11	0.00	0.02	0.00	-0.34	-0.42
			0.09	0.00	0.00	0.00	0.34	0.21
15	Aerobic Decay rate of NOBs	0.17	0.19	0.00	0.02	0.00	-0.34	-0.42
			0.15	0.00	0.00	0.00	0.34	0.21
16	Anoxic/anaerobic decay rate of NOBs	0.08	0.09	0.00	0.02	0.00	-0.34	-0.21
			0.07	0.00	0.00	0.00	0.00	0.21
17	Max spec growth rate of AAOs	0.2	0.22	0.00	0.00	0.00	0.00	0.00
			0.18	0.00	0.00	0.00	0.00	0.00
18	Substrate (NH4) halfsaturation of AAOs	2	2.20	0.00	0.00	0.00	0.00	0.00
			1.80	0.00	0.00	0.00	0.00	0.00
19	Substrate (NO2) halfsatturation of AAOs	1	1.10	0.00	0.00	0.00	0.00	0.00
			0.90	0.00	0.00	0.00	0.00	0.00
20	Aerobic Decay rate of AAOs	0.019	0.02	0.00	0.00	0.00	0.00	0.00
			0.02	0.00	0.00	0.00	0.00	0.00
21	Anoxic/anaerobic decay rate of AAOs	0.0095	0.01	0.00	0.00	0.00	0.00	0.00

No.	Kinetic Parameters	Default Value	1% Chagenged Value (+ , -)	% Change of BOD Effluent	% Change of COD Effluent	% Change of TSS Effluent	% Change of TN Effluent	% Change of TP Effluent
			0.01	0.00	0.00	0.00	0.00	0.00
22	Max spec growth rate of PAOs	0.95	1.05	0.00	0.00	0.00	0.34	0.00
			0.86	0.00	0.00	0.00	-0.34	-0.21
23	Max spec growth rate P-limited of PAOs	0.42	0.46	0.00	0.00	-0.09	0.68	0.00
			0.38	0.00	0.00	0.00	2.05	0.00
24	Substrate (Phb/Zbp) halfsat of PAOs	0.1	0.11	0.00	0.00	0.00	0.00	-0.21
			0.09	0.00	0.02	0.00	0.00	0.00
25	Substrate (Phb/Zbp) halfsat. (P-limited) of PAOs	0.05	0.06	0.00	0.00	0.00	-0.68	0.00
			0.05	0.00	0.00	0.00	0.34	0.00
26	Anoxic/anaerobic decay rate of PAOs	0.1	0.11	-0.31	-0.22	-0.54	9.93	-2.31
			0.09	0.31	0.17	0.54	-10.27	2.31
27	Anaerobic decay rate of PAOs	0.04	0.04	0.00	0.00	0.00	0.34	-0.21
			0.04	0.00	0.02	0.00	-0.68	0.00
28	Sequestration Rate of PAOs	4.5	4.95	0.00	0.46	0.36	-8.90	3.57
			4.05	0.00	-0.61	-0.62	12.67	-3.99
29	Anoxic growth factor of PAOs	0.33	0.36	0.00	-0.02	-0.18	3.42	-0.42
			0.30	0.00	0.02	0.09	-3.42	0.21

Table F-3 Sensitivity Analyses Results of Settling Parameters

No.	Settling Parameters	Default Value	1% Chagenged Value (+ , -)	% Change of BOD Effluent	% Change of COD Effluent	% Change of TSS Effluent	% Change of TN Effluent	% Change of TP Effluent
1	Maximum Vesilind Settling Velocity	170	187	0.00	0.00	0.00	0.00	0.00
			153	0.00	0.00	0.00	0.00	0.00
2	Vesilind Hindered zone settling	0.37	0	0.00	0.00	0.00	0.00	0.00
			0	0.00	0.00	0.00	0.00	0.00
3	Clarification switching function	100	110	0.00	0.00	0.00	0.00	0.00
			90	0.00	0.00	0.00	0.00	0.00
4	Specified TSS Concantration for height calculation	2500	2750	0.00	0.00	0.00	0.00	0.00
			2250	0.00	0.00	0.00	0.00	0.00
5	Max compactability constant	15000	16500	0.00	0.00	0.00	0.00	0.00
			13500	0.00	0.00	0.00	0.00	0.00
6	% Solid Removal of Clerifier	99.8	99.9	-38.58	-11.72	-48.97	-4.79	-6.51
			99.7	37.96	11.31	47.10	4.45	6.09

Appendix G. Bursa Model Data Used for Validation

Table G-1 Inputs and Effluent Data Used in Validation Calculations Adapted from 2017 Annual Report (Personal Communications, 2019)

2017 Montly Data	Flow rate (m^3/d)	Influent							Effluent					Operational Parametres		
		pH	ºC	COD mg/l	TSS mg/l	BOD5 mg/l	TN mg/l	TP mg/l	COD mg/l	BOD5 mg/l	TSS mg/l	TN mg/l	TP mg/l	WAS (m^3/day)	RAS (m^3/day)	IR (%)
Junary	246,644	8.0	15.0	571.9	348.5	233.0	55.9	9.4	21.6	4.6	5.3	5.1	1.0	8,877	259,512	268%
February	242,976	8.1	16.4	627.7	359.5	263.7	59.6	10.2	23.8	5.0	5.7	3.1	0.9	7,748	238,114	246%
March	265,400	8.3	17.9	662.5	402.5	268.8	57.3	9.1	25.7	5.4	6.1	3.3	0.7	10,194	265,404	257%
April	241,454	8.2	18.5	591.3	384.6	241.0	49.9	8.2	23.7	4.9	5.8	3.1	0.5	10,182	253,206	265%
May	264,290	8.1	20.8	505.9	298.8	203.7	49.0	7.7	25.5	5.3	6.4	4.5	0.5	11,798	260,899	251%
June	269,590	8.0	22.8	510.1	308.1	205.3	49.0	7.0	25.1	5.2	5.7	4.6	0.8	9,837	248,691	239%
July	279,809	7.8	25.3	555.1	301.4	228.1	59.8	8.5	28.1	5.5	6.7	3.1	1.2	9,078	261,222	237%
August	260,451	7.5	26.8	860.6	398.8	354.0	59.1	10.1	37.0	7.6	9.8	2.6	1.2	9,797	276,678	254%
September	207,731	8.0	26.1	721.7	375.3	300.8	59.8	9.1	30.7	6.7	8.4	2.2	1.3	8,317	243,245	297%
October	235,447	8.2	24.9	800.2	459.5	313.9	64.9	10.9	33.6	7.1	8.3	2.3	0.8	10,018	275,426	279%
November	226,350	8.1	21.2	698.1	357.9	280.6	67.4	9.9	33.2	6.8	10.7	2.4	1.2	8,941	239,345	279%
December	251,764	8.1	21.3	595.3	323.5	241.4	58.6	8.7	27.8	5.7	6.7	3.5	1.2	8,693	239,010	258%
Average	249,325	8.0	21.4	641.7	359.9	261.2	57.5	9.1	28.0	5.8	7.1	3.3	0.9	9,457	255,063	261%