INVESTIGATION OF
ECONOMIC AND ENVIRONMENTAL IMPACTS OF
THE USE OF SOLAR AND BIOGAS RESOURCES
IN URBAN WASTEWATER TREATMENT PLANTS

KENTSEL ATIKSU ARITMA TESİSLERİNDE
GÜNEŞ VE BİYOGAZ ENERJİ KAYNAKLARI KULLANIMININ
EKONOMİK VE ÇEVRESEL ETKİLERİNİN İNCELENMESİ

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This work titled **"Investigation of Economic and Environmental Impacts of the Use of Solar and Biogas Resources in Urban Wastewater Treatment Plants"** by **GÖZDE ODABAŞ** has been approved as a thesis for the Degree of Master of Science in **Clean Renewable Energies** by the Examining Committee Members mentioned below.

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I declare that

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- All audio-visual and written information and results have been presented according to the rules of scientific ethics
- in case of using others works, related studies have been cited in accordance with scientific standards
- all cited studies have been fully referenced
- I did not do any distortion in the data set
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17/09/2019

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ABSTRACT

INVESTIGATION OF ECONOMIC AND ENVIRONMENTAL IMPACTS OF THE USE OF SOLAR AND BIOGAS RESOURCES IN URBAN WASTEWATER TREATMENT PLANTS

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September 2019, 121 pages

As water and energy are the most basic needs for the well-being of people, the water-energy nexus is an area to be examined. A large share of the energy demand (ED) of the water sector is caused by Wastewater Treatment Plants (WWTP) and realizes in the form of electricity constituting a large share of their operating costs. Considering the world's dependence on fossil fuels, Green House Gases (GHGs) caused by electricity generation and the current climate change crisis, it is an important opportunity to meet ED of WWTPs by renewable energy sources (RES).

The wastewater industry has developed rapidly in the last 20 years in Turkey. ED of the sector has increased as a result of the need for more advanced technologies and treatment methods due to the increasing number and capacity of WWTP, per capita wastewater and population. It will continue to increase due to plants in construction and the increase of population. In this study, together with the option of RES integration in WWTPs, ED to treat 1 m^3 of wastewater (energy intensity-EI-kWh /m^3) in the WWTPs in metropolitan municipalities, which are the source of 85% of the total wastewater produced and host 70% of the WWTPs in Turkey, was investigated. The main objective of this study is to calculate the EI based on type and process of WWTPs in Turkey and to analyze possible environmental and economic impacts of meeting the ED via photovoltaic (PV) panels and biogas generators.

In the first stage of the study, an online survey was prepared to collect information from WWTPs. The first part of the survey has questions related to the ED of the plant; the second part focuses on the perception of WWTPs regarding the use of RES. In addition, data regarding WWTPs in metropolitan municipalities, treated wastewater, ED, (if available) biogas and electricity generation, population served, BOD/COD/SS, type of plant and treatment process were collected from various open sources. The data that cannot be obtained online has been completed via personal communication for 451 plants. Data collected for 2017 were analyzed based on plant type, the process used and the amount of treated wastewater. The analysis revealed that the EI of large-scale WWTPs is lower than that of small-scales. Furthermore, as expected, the EI of the primary treatment (0.07 - 0.34 kWh / m^3) is lower than that of secondary (0.08 - 1.36 kWh / m^3) and advanced treatment (0.15 - 0.99 kWh / m^3).

In the second stage of the study, 25 WWTPs were selected according to the completeness of their data and representing different capacities. The possibility of meeting their ED by biogas and solar power and the economic and environmental impacts of this integration were investigated. HOMER simulation software was used in six scenarios defined based on CO_2 emission penalty (0 and 16 $/ton) and electricity selling price (0.000, 0.050 and 0.133 $/kWh). The results were examined under five WWTP capacities. The analysis has shown that RES integration is not cost-effective for WWTPs having a capacity of below 1 million m^3. It was observed that CO_2 penalty and electricity selling have a major impact on the generation from the RES and the in-use of generated electricity for WWTPs having a capacity of above 1 million m^3. In the case of electricity selling price of 0.133 $/kWh, RES can meet 88% of the ED, while PV panel can generate an amount equal to 3.1 times the ED. In the scenario where there is no electricity selling and emission penalty, CO_2 emissions can be mitigated by 15% while production from RES reached up to 23%.

Keywords: Urban wastewater treatment plant, energy intensity, renewable energy, solar, PV, sludge, biogas, HOMER

ÖZET

KENTSEL ATIKSU ARITMA TESİSLERİNDE GÜNEŞ VE BİYOGAZ ENERJİ KAYNAKLARI KULLANIMININ EKONOMİK VE ÇEVRESEL ETKİLERİNİN İNCELENMESİ

Gözde ODABAŞ

Yüksek Lisans, Temiz Tükenmez Enerjiler Anabilim Dalı

Tez Danışmanı: Doç. Dr. Merih AYDINALP KÖKSAL

Eylül 2019, 121 sayfa

Su ve enerji insanların refahı için en temel ihtiyaçlar iken, su-enerji ilişkisi incelenmesi gereken bir alandır. Su sektörünün enerji ihtiyacının büyük bir kısmı Atıksu Arıtma Tesislerinde (AAT) ve elektrik formunda gerçekleşerek işletme maliyetlerinin büyük bir kısmını oluşturmaktadır. Dünyanın bağımlı olduğu fosil yakıtlar ile elektrik üretiminin sebep olduğu sera gazları ve günümüzde yaşanan iklim değişikliği krizi düşünüldüğünde AAT'lerin elektrik ihtiyacının yenilenebilir enerji kaynaklarından (YEK) elde edilmesi önemli bir fırsattır.

Atıksu sektörü Türkiye'de son 20 yılda hızla gelişmiştir. Artan AAT sayısı ve kapasitesi, kişi başı oluşan atıksu ve nüfusun etkisiyle daha gelişmiş teknolojiler ve arıtma yöntemlerine ihtiyaç duyulması neticesinde sektörün enerji talebi artmıştır. Yeni yapılması planlanan tesisler ile nüfusun da etkisiyle artmaya devam edecektir. Bu çalışmada, Türkiye'deki AAT'lerin %70'ini barındıran ve Türkiye'de oluşan toplam atıksuyun %85'inin kaynağı olan büyükşehir belediyelerine ait AAT'lerin 1 m^3 atıksu arıtımı için ihtiyaç duydukları elektrik (enerji yoğunluğu-kWh/m^3) ile AAT'lere YEK entegrasyonu seçeneği araştırılmıştır. Çalışmanın temel amacı, Türkiye'de AAT türüne ve kullanılan yönteme göre enerji yoğunluğunun hesaplanması ve ihtiyaç duyulan elektrik talebinin fotovoltaik panel ve biyogaz jeneratörü ile elde edilmesinin olası çevresel ve ekonomik etkilerinin incelenmesidir.

Çalışmanın ilk aşamasında AAT'lerden bilgi toplamak üzere çevrimiçi anket hazırlanmıştır. Anketin ilk bölümünde tesisin enerji tüketimine yönelik sorular yer alırken, ikinci bölümünde AAT'lerin YEK kullanımına yönelik algısı ele alınmıştır. Ayrıca çeşitli açık kaynaklardan büyükşehirlerde yer alan AAT'ler ve arıtılan atıksu, enerji tüketimi, (varsa) biyogaz ve elektrik üretimi, hizmet verilen nüfus, BOİ/KOİ/AKM, tesisin türü ve arıtma prosesi bilgileri toplanmıştır. Çevrimiçi elde edilemeyen bilgiler birebir iletişim aracılığıyla 451 tesis için büyük oranda tamamlanmıştır. 2017 yılına ait toplanan veriler tesis türü, kullanılan proses ve arıtılan atıksu miktarına göre analiz edilmiştir. Analiz, büyük ölçekli AAT'lerin enerji yoğunluğunun küçük ölçeklilerden düşük olduğunu ortaya koymuştur. Ayrıca, beklenildiği üzere birincil arıtma türünün enerji yoğunluğunun (0,07 – 0,34 kWh/m^3) ikincil (0,08 – 1,36 kWh/m^3) ve ileri arıtma (0,15 – 0,99 kWh/m^3) türlerinden düşük olduğu görülmüştür.

Çalışmanın ikinci aşamasında, verilerinin bütünlüğüne ve farklı kapasiteleri temsil etmelerine göre seçilen 25 AAT'nin elektrik talebinin biyogaz jeneratörü ve fotovoltaik panel aracılığıyla karşılanması ve bu entegrasyonun ekonomik ve çevresel etkileri araştırılmıştır. CO_2 salım cezası (0 $/ton ve 16 $/ton) ve elektrik satış fiyatı (0,000 $/kWh, 0,050 $/kWh ve 0,133 $/kWh) bazında olmak üzere 6 senaryo kapsamında HOMER simülasyon yazılımı kullanılmıştır. Sonuçlar 5 farklı AAT kapasitesi altında incelenmiştir. İncelemeler, 1 milyon m^3 altındaki AAT'ler için YEK entegrasyonunun maliyet etkin olmadığını göstermiştir. CO_2 emisyon cezası ve elektrik satışının 1 milyon m^3 üzerindeki AAT'lerin YEK'ten elektrik üretimini ve üretilen elektriğin tesis içinde kullanımını büyük oranda etkilediği görülmüştür. Elektriğin 0.133 $/kWh'e satılması durumunda elektrik ihtiyacının ortalama %88'i YEK ile karşılanabilirken, aynı senaryoda fotovoltaik panel elektrik ihtiyacının 3,1 katını üretilebilmektedir. Elektrik satışı ve karbon emisyon cezası olmadığı senaryoda ise %23'e varan oranlarda YEK'ten üretim yapılırken CO_2 emisyonu %15 azaltılabilmiştir.

Anahtar Kelimeler: Atıksu arıtma tesisi, enerji yoğunluğu, yenilenebilir enerji, güneş enerjisi, FV, arıtma çamuru, biyogaz, HOMER

TEŞEKKÜR

Tez çalışmamız boyunca engin bilgi ve tecrübelerinden yararlandığım, sadece bilimsel anlamda değil, sahip olduğu eşsiz bilgisiyle desteğini benden esirgemeyerek her zaman anlayış gösteren ve motivasyon veren değerli hocam Sayın Doç. Dr. Merih AYDINALP KÖKSAL'a,

Uzakta da olsalar desteklerini hep hissettiğim, en zor anımda hep yanımda olan, motivasyon sağlamak için ellerinden gelen her şeyi yapan, beni benden çok düşünen canlarım annem Ayla, babam Hayrettin, kardeşim Mert'e,

Tez dönemi tecrübesiyle bana bu süreçte yol gösteren, on bir yılda birlikte büyüdüğümüz, şu an olduğum insan olmamı sağlayan, hayatımdaki her şeydeki payı ile beni hep geliştiren, kafa dengim, ruh eşim, kardeşim Elif'e,

Her zamanki sabrından tez dönemimde de bir şey kaybetmeden bütün, anlayışıyla bana destek olan, yardımıma koşan, bütün kaynaklarını seferber eden, tecrübe ve bilgisiyle yol gösteren, moral ve en çok da sevgi veren hayat arkadaşım Dursun'a,

Yüksek lisans eğitimim boyunca bana sonsuz anlayış gösteren ve hep destekleyen, yeri gelince benim yerime çalışan, profesyonel anlamda gelişimime katkı sağlayan, hep bir şeyler öğrendiğim çalışma arkadaşlarım Duygu KURAL, Pınar AKPINAR, Onur AKPULAT, Rifat Ünal SAYMAN ve Tulû TOHUMCU'ya,

Evde tez döneminde biriyle birlikte yaşamak durumunda kalan ve bu süreçte elinden gelen maddi manevi tüm desteğiyle yanımda olan ve moral veren sevgili ev arkadaşım Neslihan'a,

Veri toplama sürecinde bana zamanının büyük bölümünü ayırıp tesisle ilgili veri ve teknik bilgiler veren atıksu arıtma tesisleri çalışanlarına,

Sonsuz teşekkürler, iyi ki varsınız…

Gözde ODABAŞ
Eylül 2019, Ankara

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ABBREVIATIONS AND SYMBOLS

Symbols

BOD_{in}	Biochemical Oxygen Demand of inflow wastewater
$BOD_{removed}$	Removed Biochemical Oxygen Demand
CO_2e	Carbon Dioxide Equivalent
COD_{in}	Chemical Oxygen Demand of inflow wastewater
$COD_{removed}$	Removed Chemical Oxygen Demand
N	Nitrogen
P	Phosphorus

Abbreviations

A2O	Anaerobic/Anoxic/Oxic
AAR	Annual Activity Report
AD	Anaerobic Digester
AL	Aerated Lagoon
AP	Aerated Pond
BOD	Biochemical Oxygen Demand
CAS	Conventional Activated Sludge
CHP	Combined Heat and Power
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
DSWWD	Deep-Sea Wastewater Discharge
EAAS	Extended Aeration Activated Sludge
EC	Energy Consumption
EI	Energy Intensity (kWh/m^3)
EMRA	Energy Market Regulatory Authority
EP	Electricity Production
EU	European Union
GHG	Greenhouse Gas

GHI	Global Horizontal Irradiance
HC	Hydrocarbons
HOMER	Hybrid Optimization Models for Energy Resources
IEA	International Energy Agency
IRENA	International Renewable Energy Agency
KPI	Key Performance Indicator
LHV	Lower Heating Value
MBR	Membrane Bioreactor
MM	Metropolitan Municipality
MoEU	Ministry of Environment and Urbanization
Mtoe	Million tons of oil equivalent
N/A	Not Applicable/Not Available
NOCT	Nominal Operating Cell Temperature
NO_x	Nitrous Oxides
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
OD	Oxidation Ditch
PE	Population Equivalent
PESR	Provincial Environmental Status Reports
PM	Particulate Matter
PV	Photovoltaic
RA	Regression Analysis
RBC	Rotating Biological Contactor
RES	Renewable Energy Source
REP	Renewable Energy Production
SBR	Sequencing Batch Reactor
SO_2	Sulfur Dioxide
SP	Stabilization Pond
SSF	Slow Sand Filtration
STC	Standard Test Condition
TF	Trickling Filter
TS	Total Solids

Turkstat	Turkish Statistical Institution
TWW	Treated Wastewater
USA	United States of America
VS	Volatile Solids
WSA	Water and Sewerage Administration
WTP	Water Treatment Plant
WW	Wastewater
WWTP	Wastewater Treatment Plant
YEKDEM	Renewable Energy Resources Support Mechanism

1 INTRODUCTION

In this chapter, background information on the energy consumption of water processes in Turkey and the world is briefly provided. General information on water-energy nexus, total energy consumption, and its sectoral distribution in Turkey and the world, the current situation of Turkish wastewater treatment is provided in the following three sections. Finally, the problem which is investigated throughout this thesis study together with the objective, scope, and structure of this thesis is presented in the following sections.

1.1 Background Information

We live in a fossil fuel dependent society with the fossil fuel shares of 81% and 65.3% in energy supply and electricity generation, respectively, as of 2016 [1] (see Figure 1.1).

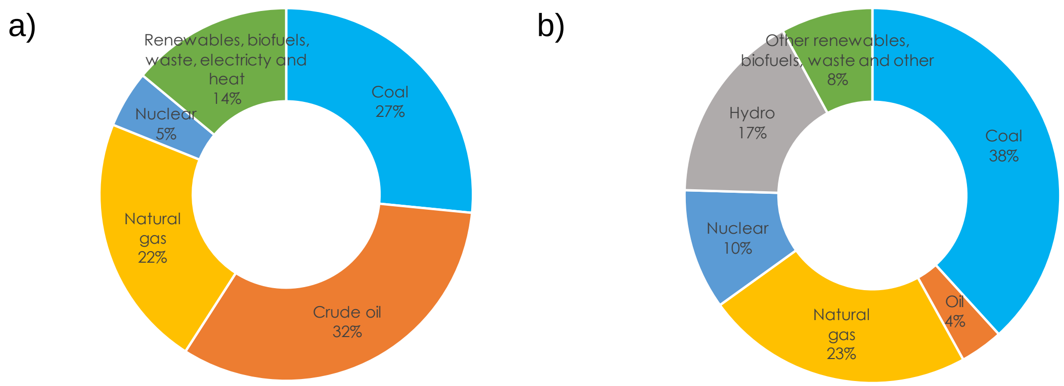


Figure 1.1. In 2016 a) Global energy supply by fuel type b) Global electricity generation by fuel type (adapted from [1])

As the process of the electricity generation from fossil fuels is basically burning the fuel to use the resulted heat, it requires a cooling agent which is a huge amount of water *i.e.* up to 4500 L per MWh of generated electricity [2]. Besides, water is not only used in cooling but also in the extraction and processing of fossil fuels. In total, 10% of global water withdrawals result from the processes of the energy sector [3].

On the other hand, since energy is used in almost every process, water processes such as water extraction, desalination, treatment, distribution, and wastewater collection and treatment, including primary, secondary and advanced, also require energy (see Figure 1.2). In 2014, the International Energy Agency (IEA) estimates that 120 Mtoe, which is nearly equal to Australia's total energy demand, was globally consumed at the water sector [3].

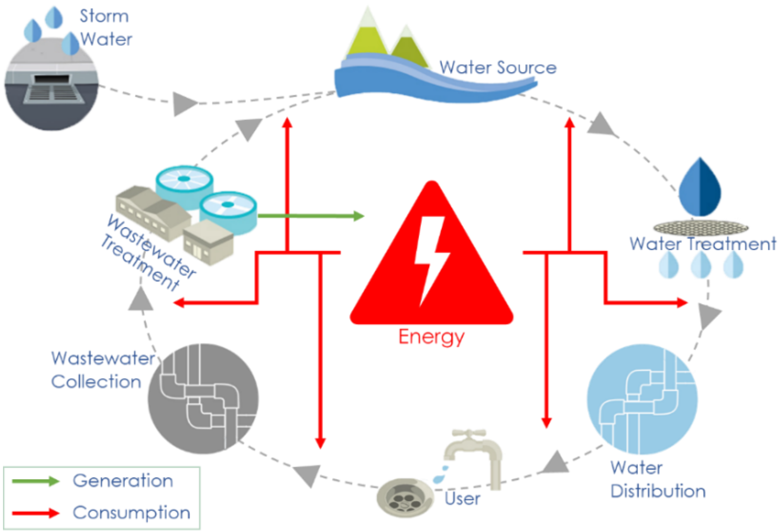


Figure 1.2. Energy usage in water processes (adapted from [4])

Energy and water, the two factors of human beings' welfare, are strongly interrelated and create a nexus called "water-energy nexus".

1.2 Overview of Water-Energy Nexus

As the rest of the world (see Figure 1.1), Turkey is also dependent on, with a ratio of 68%, fossil fuels to generate electricity (see Figure 1.3.a).

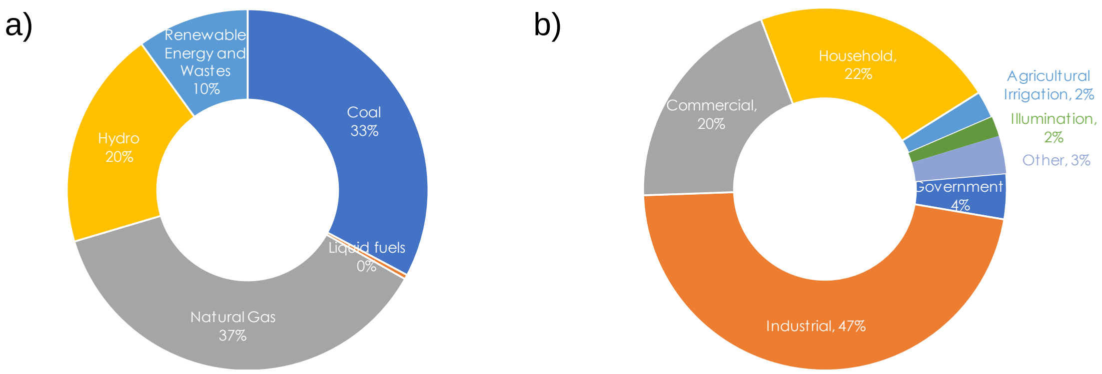


Figure 1.3. In 2017 a) Electricity generation by fuel type in Turkey b) Electricity consumption by sector in Turkey (adapted from [5])

In 2017, Turkey's total electricity consumption was 249,023 GWh and Figure 1.3.b. shows the sectoral distribution of the total electricity consumption [5]. The category named “other” includes electricity consumption in livestock, fishery sector, and municipal water abstraction pumping facilities, and other public services, *etc*. It can be concluded that the water sector in Turkey is also consuming around 2.5%-3% of the total electricity consumption in Turkey. Similarly, IEA World Energy Outlook Report indicates that 60% (820 TWh) of the energy demand in the water sector is attributable to electricity demand and comprises 4% of the global electricity consumption [3]. Water extraction, distribution, and wastewater treatment is 40%, 20%, and 25%, respectively, of the total electricity consumption for water [3].

The amount of energy consumption of water processes depends on various factors such as geography, the composition of the water and wastewater, the technology and the processes used in the water/wastewater treatment plants [6]–[9]. That is why it differs not only among countries or cities but also among the treatment plants within the same city.

1.3 Current Situation of Wastewater Treatment in Turkey

Based on 2016 data, 16% of Turkey’s total population does not have access to sewage collection services, as 30% does not have access to wastewater treatment plant (WWTP) services [10]. In European countries, this ratio is less than 20% [11].

As of 2016, there are 881 WWTPs in Turkey with a total capacity of 5.9 billion m^3 and 4.5 billion m^3 wastewater was discharged (treated and untreated) [10]. The increase in the number and capacity of WWTP has been significant especially in the last 15 years (see Figure 1.4 and Figure 1.7).

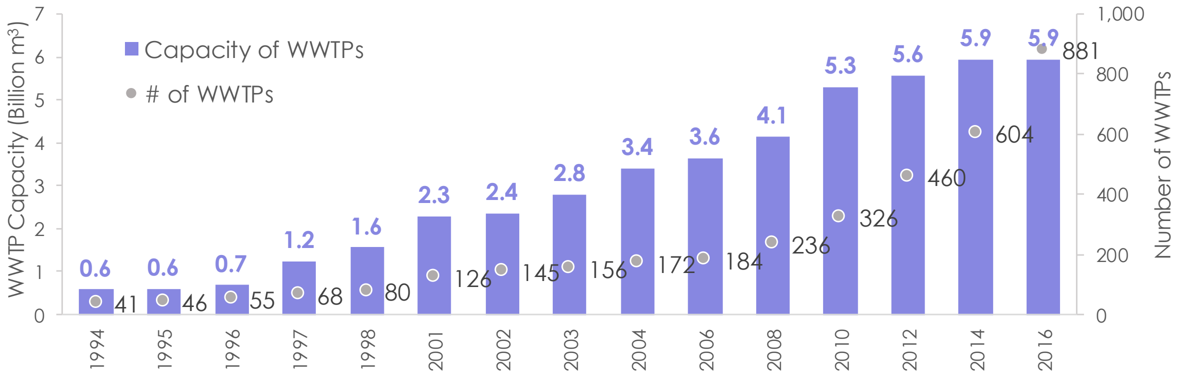


Figure 1.4. Total capacity and number of WWTPs in Turkey (adapted from [10])

The number of WWTPs in each city is presented in Figure 1.5. As can be seen in the figure, the number of WWTP in each city increases from the east of the country to the west.

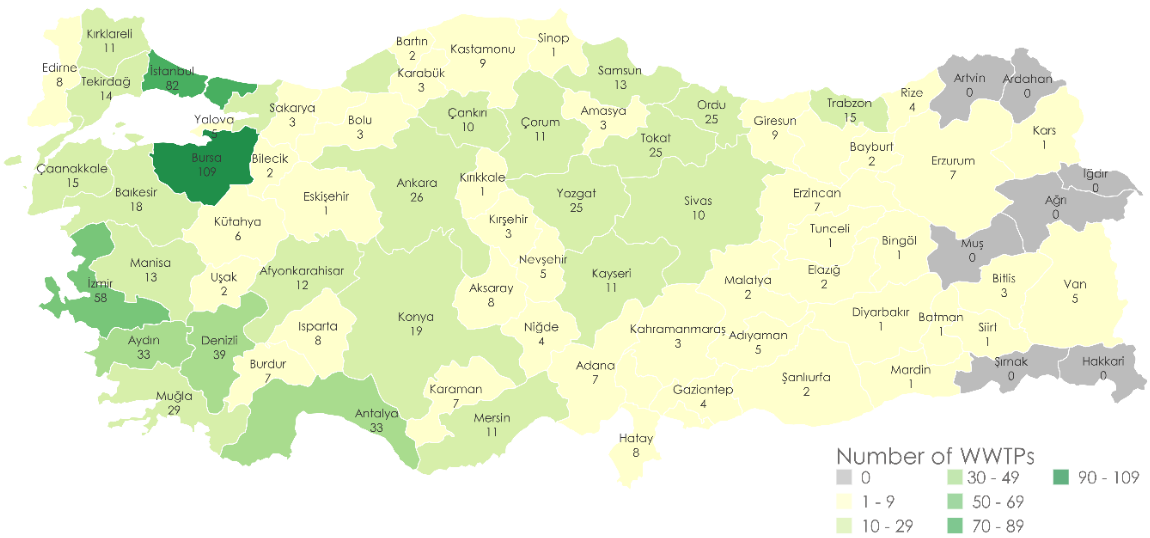


Figure 1.5. Total number of wastewater treatment plants in cities (adapted from [10])

The total discharged wastewater (treated and untreated) in Turkey has increased by 197% between 1994 and 2016, however, it cannot be explained by only population growth. Discharged wastewater per capita also risen by 45% in this period [10] as can be seen in Figure 1.6.

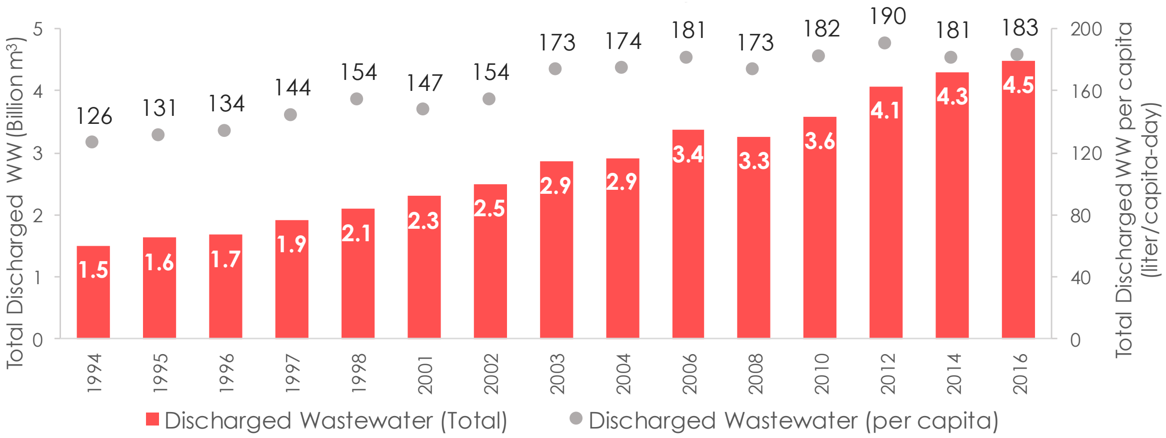


Figure 1.6. Discharged wastewater in Turkey (total and per capita) (adapted from [10])

Treated wastewater ratio has also been increased from 10% to 86% in the same period (see Figure 1.7).

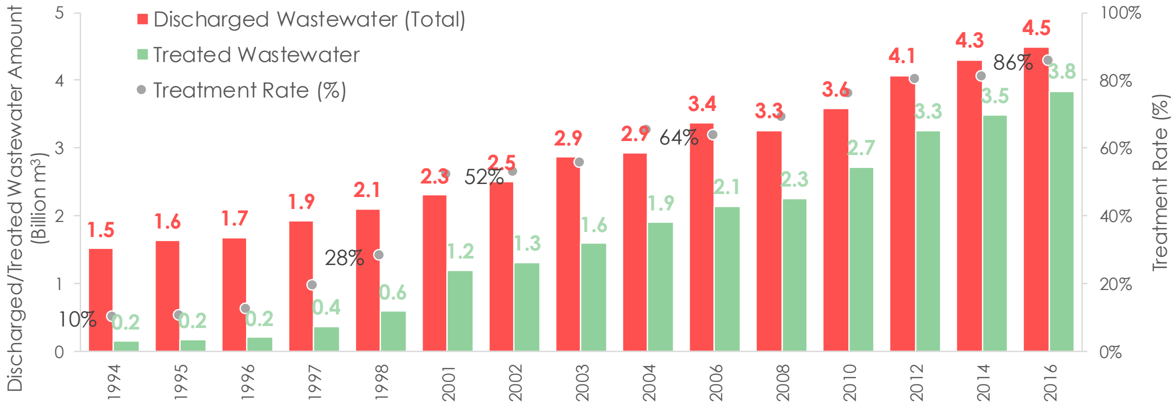


Figure 1.7. Discharged and treated wastewater in Turkey (adapted from [10])

85% of the wastewater discharge in Turkey is in metropolitan municipalities (MMs) and 70% of the WWTPs belong to MMs while 89% of the total treated wastewater is again in MMs (see Figure 1.8 and Figure 1.9).

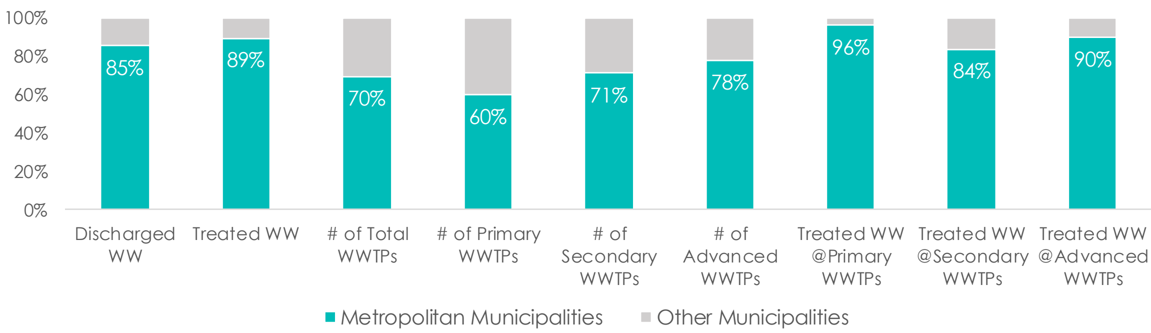


Figure 1.8. Wastewater statistics for metropolitan and other municipalities (2016) (adapted from [10])

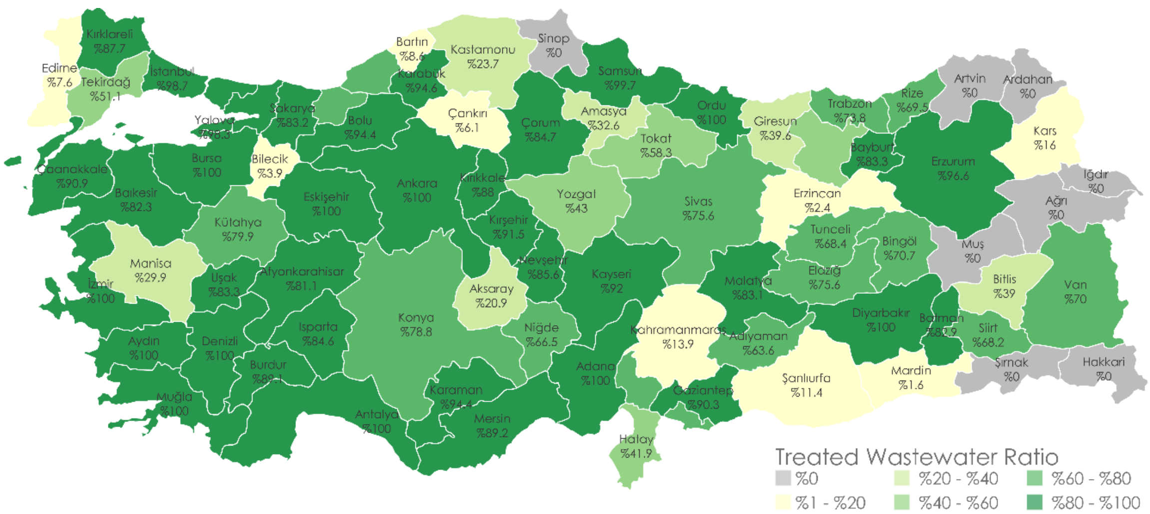


Figure 1.9. Treated wastewater ratio in cities of Turkey (adapted from [10])

Wastewater treatment in Turkey categorized into five levels as follows:

- ✓ Natural Treatment: A simple plant-based on natural filtration of the wastewater [12].
- ✓ Primary (Physical) Treatment: Plant with only one sedimentation process to remove rough solid materials from the wastewater.
- ✓ Secondary (Biological) Treatment: Plant with the removal of organic matter using a biological process and a final sedimentation tank.
- ✓ Advanced (Tertiary and/or Chemical) Treatment: Secondary treatment plant with nitrogen and phosphorus removal processes added.
- ✓ Package Treatment: Small scale secondary treatment plant.

Figure 1.10 represents the number of WWTPs and the treated wastewater in each treatment type from 2010 to 2016. It is clearly seen that the majority of the WWTPs are secondary treatment while most of the wastewater is treated in advanced WWTPs in both 2010 and 2016 (see Figure 1.10). Almost half of the treated wastewater is treated by advanced WWTPs while 24% is by primary WWTPs [10].

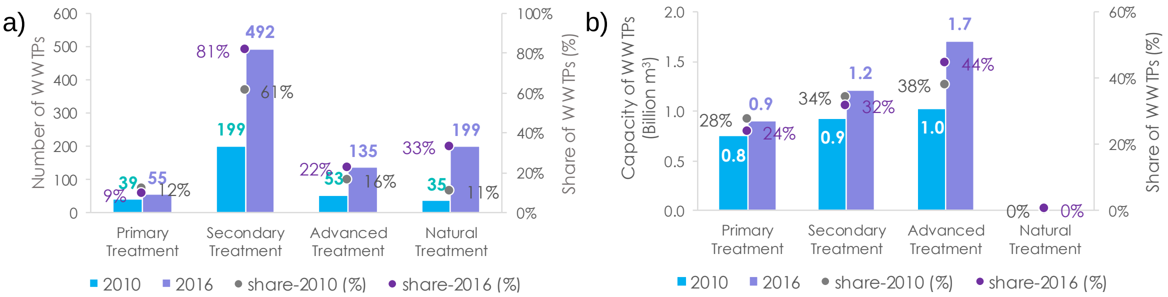


Figure 1.10. a) The number of wastewater treatment plants by type in 2010 and 2016 b) The amount of treated wastewater by treatment type in 2010 and 2016 (adapted from [10])

1.4 Problem Definition

As one of the energy-intense sectors, wastewater treatment has environmental, economic, and social impacts in addition to its significant function in protecting the environment.

Wastewater treatment directly emits CH_4 and N_2O during the treatment process. In addition, because of wastewater treatment's electricity demand and specifically the global dependence on fossil fuels for electricity generation, it indirectly causes CO_2

emissions. In total, wastewater treatment contributes to GHG emissions of a WWTP with a share of as high as 60-80% [13], [14]. The situation is similar to Turkey. 86% of the GHG emissions of Bursa Water and Sewerage Authority (WSA), for instance, is attributable to the electricity consumption of pumping stations and WWTPs [15]. In addition, stricter environmental regulations on both national and international level require investments on more energy-intensive treatment technologies than the conventional ones. As an indicator of this technical change, the rise in the amount of advanced treated wastewater is higher than the secondary ones in the period of six years in Turkey (see Figure 1.10).

Another problem associated with WWTPs is high construction and operation costs. According to IEA's Water-Energy Nexus report, it is indicated that a large share of an energy bill of a municipality might result from the energy use of WWTP [3]. Specifically, the share of the energy consumption cost changes between 25–40% in operating costs [16] while the share of the electricity consumption cost is 30% in the operation and maintenance costs based on literature and managing experience [13]. This indicates an energy intensity of 0.3–2.1 kWh/m^3 of treated wastewater [13]. For Kocaeli WSA, for example, electricity share in the operational cost differs between 20%-40% while the energy intensity differs between 0.18-0.55 kWh/m^3 for its various plants [17].

Possible increase in the water bills of the citizens due to the cost of construction and operation of WWTPs could create problem for society from the economic perspective. Lack of proper collection by sewerage and treatment of the wastewater systems could lead to water scarcity and various diseases for society from the environmental and public health perspective as wastewater treatment has relation with the disease mortality [18]. Consequently, economic and environmental problems of wastewater treatment directly create social problems as well.

As it is indicated in the previous section, the increase in total energy demand for WWTPs inevitable due to the significant increase of discharged wastewater as well as the share of the treated wastewater (see Section 1.3).

1.5 The Objective of the Thesis

It is possible to limit the increase in electricity demand of WWTPs via the implementation of efficiency and maintenance measures [19]. However, electricity consumption will still be significant and will cause the impacts highlighted above. There are pioneering municipalities both in the EU and the USA, which reduce and even neutralize these impacts by improving energy efficiency together with the deployment of renewable sources [3], [19].

The aim of this study is to reveal the reduction potential of impacts of wastewater processes in Turkey.

Two objectives have been identified to achieve this aim:

- ✓ Creating a database of the current situation regarding energy intensity (EI - kWh/m^3) of WWTPs in Turkey.
- ✓ To conduct an economic and environmental impact analysis of supplying all/part of the energy need of WWTPs with renewable sources in Turkey.

The findings and outputs of this study will be a database representing the current situation of electricity consumption and renewable energy integration potential of WWTPs for literature and decision-makers.

1.6 Scope of the Thesis

This study is based on the fact that the wastewater treatment processes are the key electricity consumers among all water processes. To prevent commercial concerns of the industry, industrial wastewater treatment plants were not included, only municipal wastewater treatment plants were considered in the study.

To achieve a conclusion for the whole of Turkey, high representation is needed. To ensure this, metropolitan municipalities were chosen because they represent 77% of the population in Turkey, 85% of the wastewater discharge and 89% of the total treated wastewater in Turkey is in MMs and 70% of the WWTPs are in MMs [10].

Another aspect of choosing metropolitan municipalities is data obtaining. Because of the İSKİ Law[1] numbered 2560 in Turkey [20], metropolitan municipalities establish a General Directorate of Water and Sewerage Administration (WSA) within them. All the treatment plants within the city are under the responsibility of WSA of the related city. Therefore, it is easy to obtain related systematic data.

The electricity consumption of wastewater collection and transfer is not considered in this study.

For renewable energy source integration in WWTPs, only PV and biogas are included thanks to their high potential and suitability for electricity generation. For PV panels, batteries are not considered because WWTPs will be grid-connected.

1.7 Structure of the Thesis

The thesis has six chapters. Chapter 1 presents the background and introductory information on water-energy nexus together with the objective and scope of the thesis. Previous studies on energy intensity (EI - kWh/m^3) of wastewater treatment processes and replacing energy sources with renewable ones are covered in Chapter 2. Chapter 3 describes the main data sources used in the thesis. Chapter 4 defines the methodology and tools to gather data and run a simulation. Chapter 4 also includes limitations and assumptions such as determining the scope, the categories of WWTPs, used parameters for economic and environmental assessments, etc. The results and discussions are provided in Chapter 5. Conclusion of the study and recommendations for future studies are included in Chapter 6.

[1] Istanbul Su ve Kanalizasyon İdaresi Genel Müdürlüğü Kuruluş ve Görevleri Hakkında Kanun (EN: Law on the Establishment and Responsibilities of General Directorate of İstanbul Water and Sewerage Administration)

2 PREVIOUS STUDIES

Energy Intensity (EI) is the key parameter for analyzing the integration of renewable energy sources (RES) into WWTPs, as the amount of energy demand which will be met should be known as the first step. EI of the WWTPs does not exist in the literature as organized data or only as one unit because of various factors, for example, the content of the wastewater, geography, climate, infrastructure, commissioning date, *etc*. [6], [8], [9], [21]. The value and the unit of EIs might differ for the same treatment methods even though the commonly used unit is kWh/m^3.

To analyze the integration of RES into WWTPs, available renewable sources for the WWTPs should be known and finally analyzed together with different additional parameters to see the impact of integration.

Following the needed steps to achieve the objective of this thesis, this chapter provides a literature review on the related topic. In the first section of this chapter, the studies on identification/assessment of energy intensity of WWTPs are summarized. The second section provides the studies on analyzing renewable energy integration to the WWTPs together with optimization of the utilization of available different RESs.

2.1 Studies on Identification/Assessment of Energy Intensity (kWh/m^3) of Wastewater Treatment Plants

In his thesis study, Ayrak [22] identified the EI of selected biological WWTPs in Turkey by using field data to reveal the relationship between the energy demand of WWTPs and the population that is served. He examined four process types *i.e.*

- trickling filter (TF),
- stabilization ponds (SP),
- classical activated sludge (CAS),
- and extended aeration activated sludge (EAAS).

It was concluded that the energy cost of the activated sludge systems is higher than other systems, while the energy cost of the EAAS system is higher than the CAS system. As can be seen in Figure 2.1, EI of the EAAS system is three times higher than that of the CAS system, eight times higher than that of the TF system, and 11 times higher than that of the SP system.

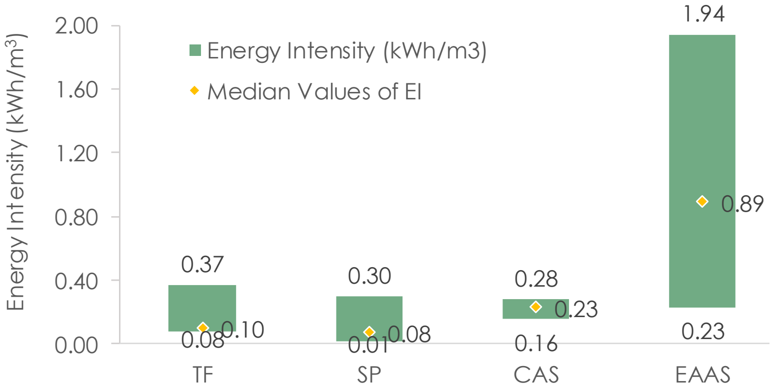


Figure 2.1. The energy intensity of WWTPs using different processes (adapted from [22])

Wakeel *et al.* [9] completed a review study for EI (kWh/m^3) of water pumping, urban water transfer, treatment of raw water and wastewater in various countries. In the study, it is revealed that the countries with the lowest EI of wastewater treatment are China and Japan, while Germany and the UK have one of the highest values (see Figure 2.2).

Figure 2.2. Energy intensity of WW treatment in different countries (adapted from [9])

However, based on the same study, it is found that the value for EI differs within the countries even for the same type of treatment systems (see Figure 2.3). This is attributable to not only the treatment methods used in the plant but also to the infrastructure of the plant [8], [9]. Maturation of the same technology used resulting in an increase in the efficiency of the process and energy also leads to variation in the EI of the same technology in different years. Richards and Schäfer presented the EI of a Spanish desalination plant as 22 kWh/m^3 in 1970; 8 kWh/m^3 in 1990, and 4 kWh/m^3 in 2010 [6].

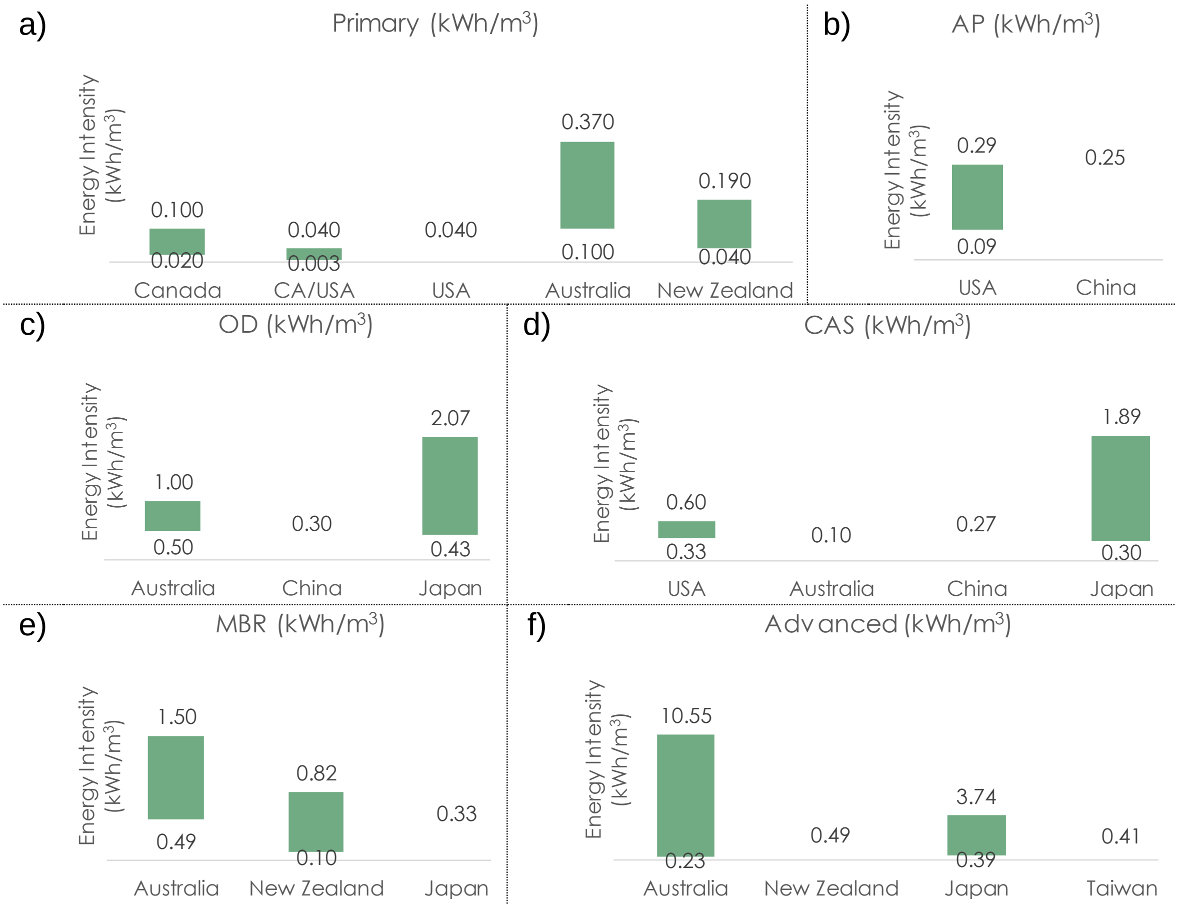


Figure 2.3. Energy intensity in different countries in a) Primary treatment b) Ponds c) Oxidation ditch d) Classical activated sludge e) Membrane bioreactor (MBR) f) Advanced treatment (adapted from [9])

Maktabifard *et al.* [23] prepared a detailed review study to investigate energy consumption of WWTPs, energy consumption reduction technologies, and energy recovery options by utilization of both internal (sludge) and external (solar, wind, *etc.*) energy sources of the WWTP. Based on their EI research, even though the similarity of the figures among countries is remarkable, China has the lowest EI in their study as well (see Figure 2.4). It was concluded that this result is attributable to two of the before mentioned reasons:

- Commissioning date: the examined WWTPs were constructed in the last 10 years
- Quality of the wastewater: the COD of the examined WWTPs ranges from 200 to 400 mg/L while it ranges from 400 to 800 mg/L in other countries.

Figure 2.4. Energy intensity (kWh/m^3) of wastewater treatment in different countries (adapted from [23])

Maktabifard *et al.* [23] also compared various energy consumption Key Performance Indicators (KPIs) other than electricity consumption per cubic meter of treated wastewater (kWh/m^3). In terms of kWh/year per population equivalent (PE), Poland has the largest value and largest variation (see Figure 2.5) while it has the lowest value for kWh/kg $COD_{removed}$, among other developed countries. On the other hand, there is not enough data for comparing the countries in terms of the values of kWh/kg $BOD_{removed}$.

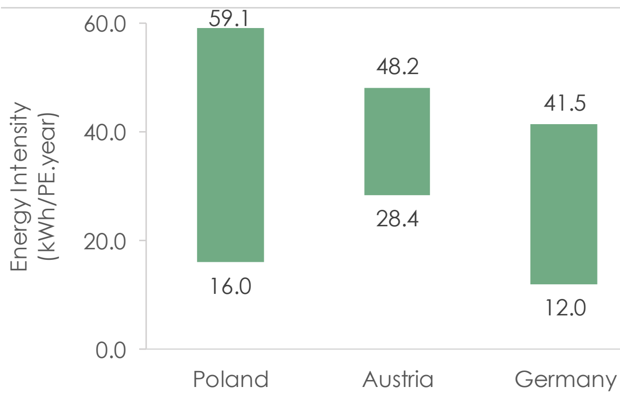


Figure 2.5. Energy intensity (kWh/PE-y) of wastewater treatment in different countries (adapted from [23])

Gu *et al.* [19] also conducted a review study on the energy intensity of wastewater treatment plants. When their common country data is compared with the Wakeel *et al.* Germany appears to have lower EI than the one in Wakeel *et al.*, while the USA and China higher one than the ones in Maktabifard *et al.* and Wakeel *et al.* (see Figure 2.2 and Figure 2.6).

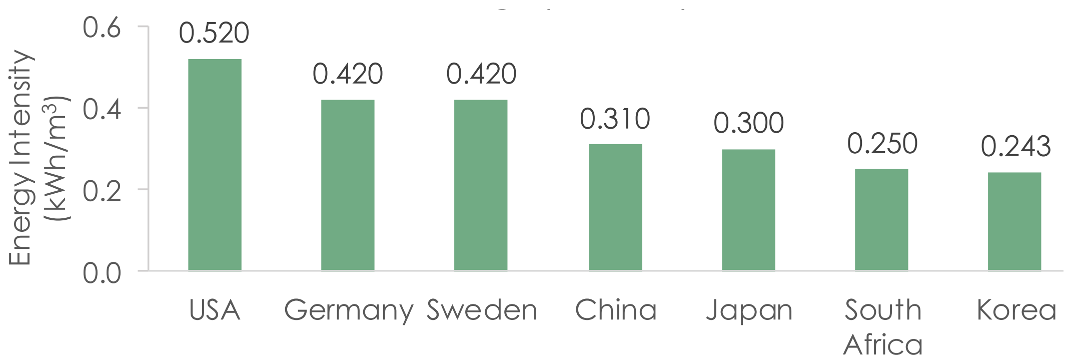


Figure 2.6. Energy intensity of wastewater treatment in different countries (adapted from [19])

In their study, they also provided the distribution of energy utilization in conventional activated sludge systems. Based on the data, the most energy-intense process is aeration with a share of 60% in total energy consumption of the processes [19]. This result is consistent with the study of Maktabifard *et al.* [23].

Within the scope of the ENERWATER project[2] [24] data of 588 WWTPs located in mainly Europe, and Asia and North America were collected. After data cleaning process, the project team conducted very detailed analysis of energy intensity by using the data of 369 WWTPs.

Energy intensities (kWh/m^3) by country and by process were one of the revealed outcomes in the study. The maximum, minimum and median values are shown in Figure 2.7. According to findings, EAAS has the highest energy intensity as well as the highest variation. The process that has the maximum energy intensity is still EAAS when their median values are compared. It is followed by MBR, CAS, and BNR.

The country with the highest EI is Spain followed by Germany and Canada. China and Japan have lower EI however Sweden has the lowest EI (see Figure 2.7).

[2] http://www.enerwater.eu/

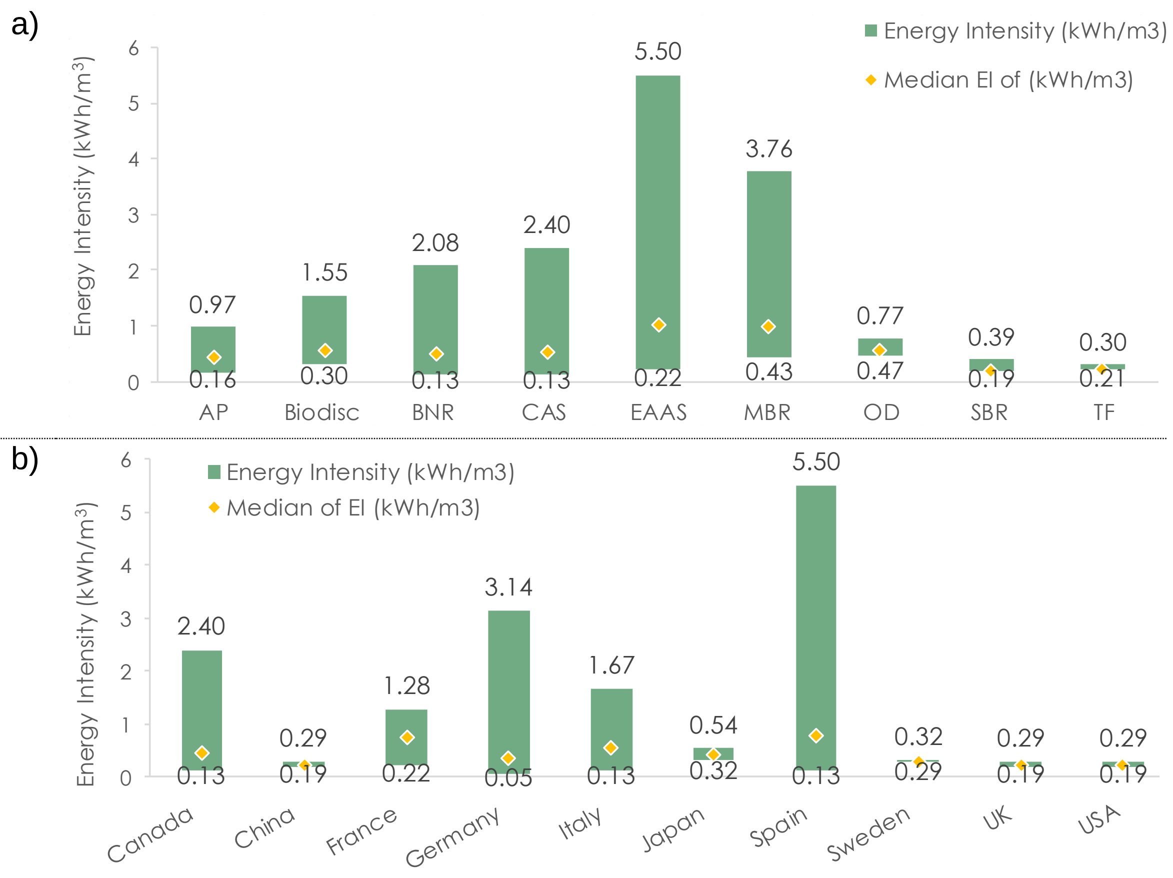


Figure 2.7. Energy intensity (kWh/m^3) a) by process b) by country (adapted from [24])

Longo *et al.* [21] present the results of their study on determining KPIs for the energy intensity of WWTPs. The study was conducted within the scope of the ENERWATER project. To provide EI values for benchmarking, they evaluated field data based on 388 of 601 WWTPs in mainly Europe, Asia, and North America, and developed a model for calculation of EI. In the study, three KPIs were defined: energy consumption per flow rate (kWh/m^3), served population (PE) (kWh/person)[3], and chemical load removal (kWh/kg $COD_{removed}$). In addition, five different benchmarking approaches under three techniques were used; normalization, statistical (Ordinary Least Squares), and programming (Stochastic Frontier Analysis, Data Envelopment Analysis, and Stochastic Data Envelopment Analysis).

[3] Based on Urban Wastewater Treatment Directive (91/271/EEC), the equivalence value is taken as 12 gN/PE.day for the study.

In the study, it has been chosen to show the results based on kWh/kg $COD_{removed}$ and it was concluded that there was a strong inverse relationship between energy intensity and population served (population equivalent-PE) (see Figure 2.8).

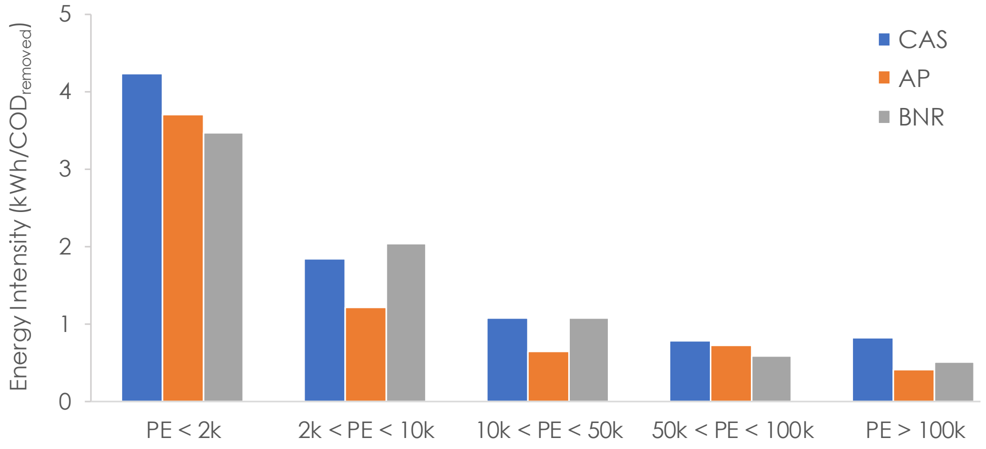


Figure 2.8. Median values of energy intensity of different treatment types (adapted from [21])

The energy intensity of different processes of the WWTP is also revealed in the study as kWh/m^3 and for various PE size. A summary is shown in Table 2.1.

Table 2.1. Upper and lower limits for the energy intensity of WWTP processes (adapted from [21])

Process	Lower Limit (kWh/m^3)	Upper Limit (kWh/m^3)
Pumping	0.022000	0.042000
Screening	0.000029	0.013000
Primary Settling	0.000043	0.000071
Aeration	0.180000	0.800000
Separation of Sludge	0.008400	0.012000
Secondary Sludge Recirculation	0.010000	0.047000
Mixing for Anoxic Reactor	0.053000	0.120000
UV Disinfection	0.045000	0.110000
Chemical Dosage Equipment	0.009000	0.015000
Tertiary Filtration	0.000740	0.002700
Sludge Treatment	0.074000	0.150000
Sludge Dewatering	0.018000	0.027000

Since a single energy intensity indicator like kWh/m^3 will be deceptive to assess and benchmark different WWTPs because of not considering the quality of inflow wastewater, Di Fraia *et al.* [25] proposed a novel method. They analyze not only basic energy performance indicators, but they also coupled it with pollution removal efficiency by using the WWTPs data produced in the ENERWATER project[2]. Based on their analysis, the Pearson coefficient of correlation (R^2) between energy consumption and rate of inflow, PE, $BOD_{removed}$ (KPI_{BOD}), and BOD_{in} (EPI_{BOD}), the correlation of energy consumption and the rate of inflow is the highest (see Table 2.2) just like in the literature while the correlation with population equivalent is the lowest.

Table 2.2. Pearson coefficient of correlation (R^2) with energy consumption (kWh/d) (adapted from [25])

	Inflow Rate (m^3/d)	Population Equivalent	$BOD_{removed}$ (kg/d)	BOD_{in} (kg/d)
Pearson coefficient of correlation (R^2) with energy consumption (kWh/d)	0.9542	0.5589	0.8091	0.8439

As a result, the authors concluded that the EPI_{BOD} is the most relevant indicator since it takes into account not only the amount of treated wastewater but also the level of need for treatment. To classify the energy performance of the WWTPs, they use the EPI_{BOD} and $BOD_{removed}$ efficiency together on the ENERWATER project data. They also tested the results in five different WWTPs in Italy (P1-P5) (see Figure 2.9).

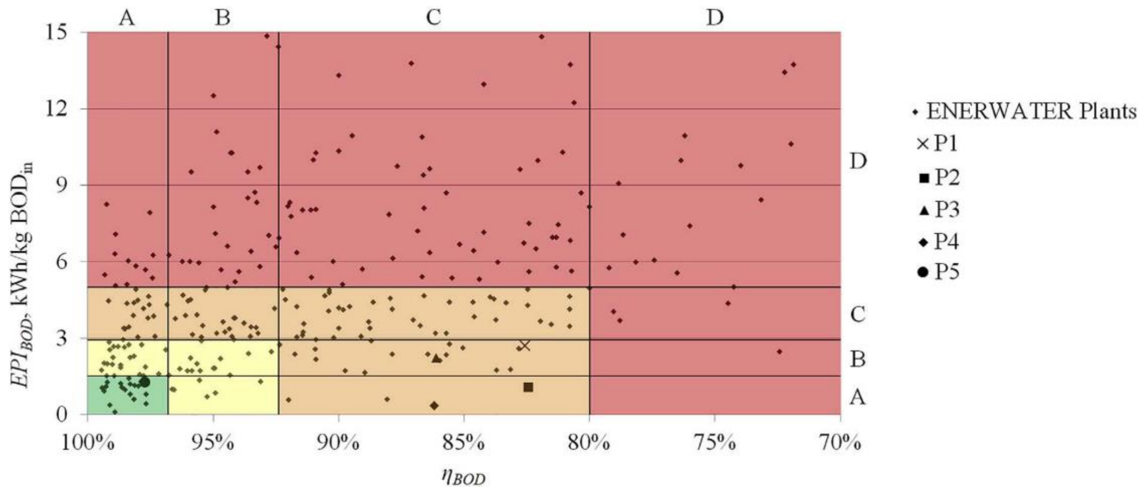


Figure 2.9. Electric energy consumption classification based on EPI_{BOD} and $BOD_{removed}$ efficiency [25]

In Japan, Mizuta and Shimada [26] studied the electricity consumption of WWTPs with oxidation ditch (OD), conventional activated sludge (CAS) with and without incineration, and advanced treatment processes such as anaerobic–anoxic–aerobic (A^2O), anaerobic–oxic, OD with nitrogen removal, pre-denitrification, and step-feed pre-denitrification. They used the data from 2004 and they ignored the ±5% outliers. Based on their study, they found out that the scale of the WWTPs is the main reason for the differences in electricity consumption.

Molinos-Senante *et al.* [27] examined the factors that impact energy intensity by using regression analysis and disclosed a formula of EI depended on these factors. Collected data of 305 WWTPs in Chile were used in order to analyze the relationship between energy intensity (kWh/PE/year) and the following parameters; wastewater flow rate (m^3/year), plant age (years), biochemical oxygen demand removal efficiency (BOD), suspended solids removal efficiency (SS), nitrogen removal efficiency (N), and phosphorus removal efficiency (P).

Following regression analysis, they implement dominance analysis and relative weight procedure to estimate the contributions of each parameter to R^2 value, which represents the relationship between the parameters and the energy intensity.

It was concluded that the dependency on the parameters changes in WWTPs employing different technologies (see Figure 2.10).

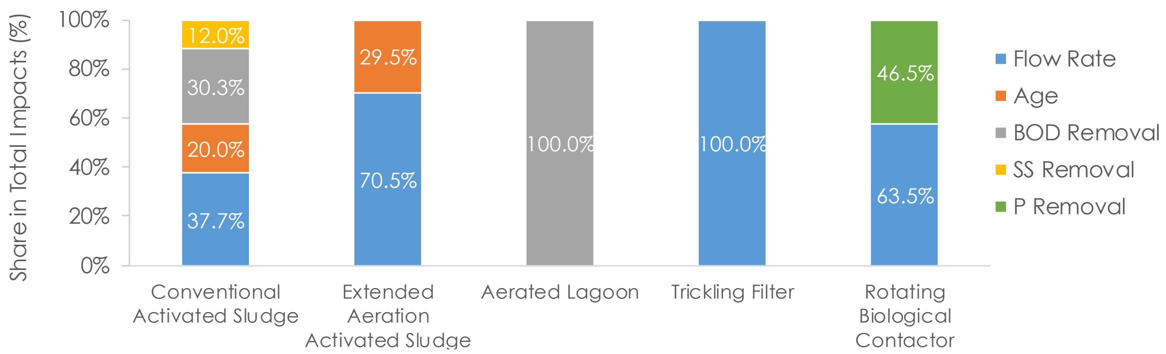


Figure 2.10. The dependency of energy intensity on various parameters for different technologies (adapted from [27])

2.2 Studies on Employment of Various Energy Sources in Wastewater Treatment Plants

Wastewater itself is assumed by some of the specialists as an energy resource because of its rich organic content, so it is sometimes assumed as “embedded energy" resource, and wastewater treatment plants are described as Water Resource Recovery Facilities (WRRF) [28] or Nutrients Energy Water factories (NEWs) [29]. That is why biogas, produced by anaerobic digestion (AD) for instance, is the first renewable energy source option that comes in one's mind for WWTPs.

Based on IEA's water and energy nexus report [3], small plants with a discharge rate less than 5,000 m^3/day are not capable of providing enough biogas to generate cost-effective electricity even though the generation of 0.56 kWh/m^3 of electricity is possible in theory. In practice, the minimum flow rate that makes WWTPs use AD increases to 22,000 m^3/day. On the other hand, based on a study of Shizas and Bagley, it was concluded that wastewater can provide a 9.3 times higher amount of energy than the required amount of energy to treat it [30]. Gude [28], in his review study, reveals the available energy forms in the wastewater (see Figure 2.11). The amount of extractable energy is 28% of the total amount of available energy.

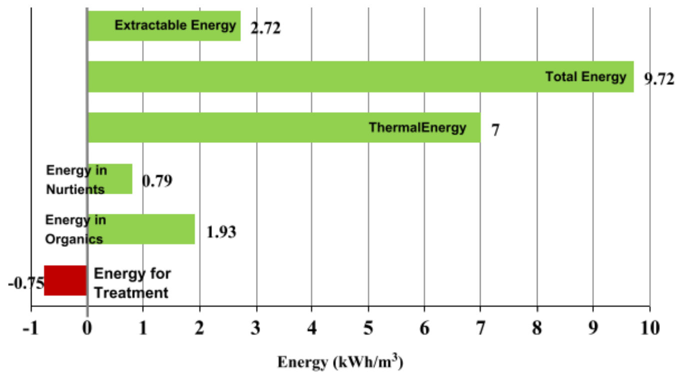


Figure 2.11. Available energy forms and quantities in the wastewater [28]

Because of its nature, biogas is the most cost-effective resource for WWTPs especially the ones above a certain size. Nevertheless, utilization of various technologies definitely will result in higher economic savings in the medium term, although higher investment in the beginning, and required to result in energy-neutrality [23]. For example, in the design of the WWTPs kinetic energy also can be an important energy source for the WWTPs on the higher level from the effluent or on the lower level from the influent.

Based on Gude's review study [28], Austria WWTP deployed a vertical axis turbine to its discharge point on where 5 m elevation from the Danube River with a flow rate of 560,000 m^3/day. The plant can generate 1,500 MWh/year of electricity which is equal to only 2.5% of the plant's demand. On contrary, Clark County WWTP in the USA can generate 85,000 MWh/year with Francis type turbines and it gains revenue from its surplus energy sell to the grid as its energy need is lower than the generated energy [28].

Gaziantep WSA [31] reported that they established an Archimedean Screw Hydro Turbine with a power of 85-170 kW at the outflow of their main WWTP of electricity. The turbine produced electricity of 560 MWh in 2017 and delivered savings of 225,000 TL (~63,000 $ with the exchange rate of 14.07.2017 [32]) based on their "Annual Activity Report" [33].

US EPA [34] published a report about various projects that integrated three different technologies i.e. solar, fuel cell and cogeneration to 11 water and wastewater treatment plants with a total capacity of 876 million m^3. It was reported that the integration resulted in the mitigation of 44 Mt CO_2 emissions and energy savings of 9.5 million dollars.

Based on the review study of Mattioli *et al.* [35], an 18 months of study in 2017 for a WWTP in Italy reveals that the co-digestion of the wastewater sludge and municipal solid waste (10 tons/day in total) increased the generation of energy to 7.8 MWh/day by doubling it, and met the 85% of the energy demand of the WWTP.

Another practical example of this application is the East Bay Municipal Utility District (EBMUD) wastewater facility. EBMUD wastewater facility [19], [28], [36] serves 685,000 inhabitants, living in the San Francisco Bay, by treating wastewater of 238,481 m^3/day. The importance of this WWTP is that it became the first net energy producer in 2012 in North America, despite the fact that providing an energy-intensive service. This was succeeded by digestion of the sewage sludge together with the food and oil waste from local restaurants, wineries, and poultry farms. Based on their 2018 Sustainability Report, the WWTP generates 130% of its electricity demand from biogas and sells its excess renewable energy to the grid [37], accomplishing saving of nearly 3 million $/year.

According to the project named "Development of Energy Efficient and Energy Positive Wastewater Treatment Plants" and conducted by TÜBİTAK MAM [38], Muğla WWTP in Turkey recovers 52% of its energy need by biogas utilization.

Hao *et al.* [29] developed a model using energy balance (consumption/recovery) based on mass balance (COD/nutrient removals) to assess the possibility of carbon neutrality for a WWTP with A^2O process in China. Through their developed method, they evaluated the recovery of;

- organic energy: anaerobic digester (AD) together with combined heat and power (CHP),
- thermal energy: water source heat pumps (WSHP),
- and solar energy: E20-327 PV panels on top of tanks.

Based on their calculation, AD&CHP can generate 53%, while the fully covered tanks with PV panels can generate 10.4% of the total energy need of the WWTP. WSHP can offset almost all the plant's energy need but since it does not directly generate in the form of electricity, it can be concluded that around 65% of the plant's electricity can be met by AD&CHP and PV panels on tanks.

Taha and Al-Sa'ed [39] selected three WWTPs in Palestine as a case study for analyzing the energy consumption, pollution removal efficiencies and renewable energy utilization. The selected WWTPs use CAS with AD, EAAS and MBR processes serve Nablus, Al-Bireh and Altira cities respectively. They assessed the PV potential of the plants, especially in the pumping stations. Based on the assessment, 9% of Al-Bireh EAAS and 15% of Altira MBR WWTPs' energy demand would be covered. In their assessment, they also included the options of on-grid and off-grid systems with six hours of battery. Al-Bireh and Altira WWTPs can recover their investment in almost four and eight years for on-grid and off-grid systems respectively. As the coverage ratio of PV system is less than 5% for Nablus CAS WWTP, the authors investigated additional options for only sludge digestion such as biogas utilization with only burner and together with CHP, and on/off-grid PV systems for aerobic digestion. When the payback periods of these four options are compared, the on-grid PV system for aerobic digestion is the lowest with almost six years. Currently used system is biogas utilization only in a burner to facilitate sludge digestion and it covers 60% of the energy consumption of the WWTP.

Chae and Kang [40] assessed the integration of three renewable energy options; namely Building Integrated PV (BIPV), small hydropower, and a heat pump for Kiheung Respia WWTP in Korea. The electricity generation was calculated by the RETScreen Clean Energy Project Analysis Software whereas thermal production was calculated manually. Based on the annual simulation results, 96 kW BIPV system can generate up to 150.7 MWh of electricity while a 10-kW small hydro turbine can generate 57 MWh of electricity. The heating pump generation was calculated as 276 MWh/year. With this integration, 6.5% of the energy consumption of the plant can be met as the demand was 7,554 MWh/year. According to their economic assessment which considers only selling to the grid, the payback period of these technologies, except BIPV, is expected to be between 6 to 7.4 years. For BIPV, the payback period is 22 years because the only option is considered and the investment cost of the BIPV is higher than the generic PV implementation.

Xu *et al.* [41] also conducted a theoretical study for a WWTP that serves 2.5 million inhabitants in eastern China. They defined a baseline scenario (Scenario A) and three alternative scenarios, which are energy consumption reduction (Energy Efficiency-EE) with combined heat and power (CHP) (Scenario B), EE with PV utilization (Scenario C), and a combined scenario of B and C (Scenario D). The scenario results for 2020 were compared. The study shows that only energy efficiency measures or only renewable energy generation systems are not enough to be energy-neutral or net energy producer. By applying both approaches will work better (see Figure 2.12).

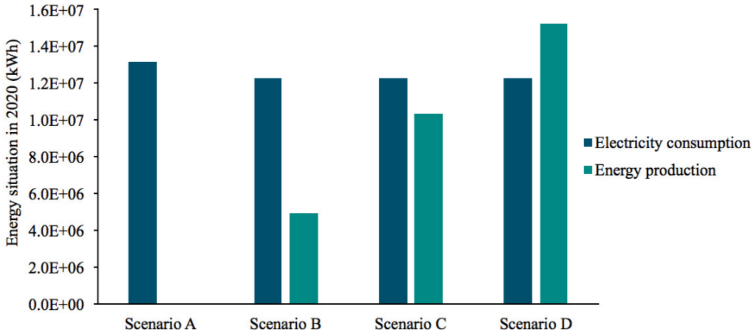


Figure 2.12. Comparison of scenarios [41]

Brandoni and Bosnjakovi [42] in 2016 revealed the optimum combination of CHP via biogas, wind turbine, and PV, by using HOMER software for a WWTP employing CAS in sub-Saharan Africa. The size of the CHP and PV ranged between 0 kW to 5 kW while the wind turbine size was chosen as 10kW based on the maximum wind speed in the area. They run the simulations under three scenarios; baseline, emergency (40 days/year black-out), and sell back to the grid. The tariff of electricity purchasing and selling changed with the scenarios. In addition, they considered the reuse of the treated wastewater for irrigation. As a result, to increase the treated wastewater quality the need to change the employed treatment technology has emerged and they included membrane bioreactor in the simulation. The load of the plant changed from 0.5 kWh/m^3 (402 MWh/year) to 3.7 kWh/m^3 (2,945 MWh/year) in the case of irrigation water generation. The theoretical calculation showed that the hybrid system can meet between 33% and 55% of the plant’s electricity demand. In case of requirement of increase in treatment quality due to irrigation purposes, electricity demand increased more than 7 times and the ratio of the support of the hybrid system dropped to 13%.

2.3 Concluding Remarks

In this chapter, some of the selected previous studies on identification/assessment methods of energy intensity (kWh/m^3) of WWTPs and utilization of RESs in WWTPs are presented. Based on the literature review, it is obvious that renewable energy integration to WWTPs is an important opportunity, both economic and environmental.

In order to identify the electricity load of the plant, which should be met by the RESs, the energy intensity parameter could be used without the exact measurement of real electricity consumption. Yet, there are variations in the energy intensity of the WWTPs based on the conducted literature review (see Table 2.3). Therefore, it was concluded that some statistical and mathematical models can be used depending on the available data set although it is hard to take one benchmarking figure to make the calculations directly.

Table 2.3. Summary of literature review on energy intensity (EI) (kWh/m^3)

Type of WWTP	Country	EI (kW/m^3)	Data Year	Source
Advanced	Japan	0.390 - 3.740	2010	[9]
Advanced	Australia	0.230 - 10.550	2016	[9]
Advanced	New Zealand	0.490	2016	[9]
Advanced	Taiwan	0.410	2016	[9]
Advanced	Austria	0.300 - 0.320	2018	[23]
Advanced	Italy	0.300	2018	[23]
Advanced	China	0.260	2018	[23]
Advanced	Poland	0.480 - 0.870	2018	[23]
Conventional	Sweden	0.480	2018	[23]
Conventional	Japan	0.320	2018	[23]
EAAS	Turkey	0.890	2010	[22]
CAS	Turkey	0.158 - 0.282	2010	[22]
CAS	USA	0.330 - 0.600	2016	[9]
CAS	Australia	0.100	2016	[9]
CAS	China	0.270	2016	[9]
CAS	Japan	0.300 - 1.890	2016	[9]
MBR	Australia	0.490 - 1.500	2016	[9]
MBR	New Zealand	0.100 - 0.820	2016	[9]
MBR	Japan	0.330	2016	[9]
MBR	Singapore	0.370 - 1.600	2018	[23]
Primary	Canada	0.020 - 0.100	2016	[9]
Primary	California	0.003 - 0.040	2016	[9]
Primary	USA	0.040	2016	[9]
Primary	Australia	0.100 - 0.370	2016	[9]
Primary	New Zealand	0.040 - 0.190	2016	[9]
OD	Japan	0.430 - 2.070	2010	[9]
OD	Australia	0.500 - 1.000	2016	[9]
OD	China	0.300	2016	[9]
AP	USA	0.090 - 0.290	2016	[9]
AP	China	0.250	2016	[9]
SP	Turkey	0.015 - 0.300	2010	[22]
TF	Turkey	0.081 - 0.372	2010	[22]
Overall	Canada	0.130 - 2.400	2015	[24]
Overall	China	0.190 - 0.290	2015	[24]
Overall	France	0.220 - 1.280	2015	[24]
Overall	Germany	0.050 - 3.140	2015	[24]
Overall	Italy	0.130 - 1.670	2015	[24]
Overall	Japan	0.320 - 0.540	2015	[24]
Overall	Spain	0.130 - 5.500	2015	[24]
Overall	Sweden	0.290 - 0.320	2015	[24]

Type of WWTP	Country	EI (kW/m^3)	Data Year	Source
Overall	UK	0.190 - 0.290	2015	[24]
Overall	USA	0.190 - 0.290	2015	[24]
Overall	USA	0.520	2017	[19]
Overall	Germany	0.420	2017	[19]
Overall	Sweden	0.420	2017	[19]
Overall	China	0.310	2017	[19]
Overall	Japan	0.300	2017	[19]
Overall	South Africa	0.250	2017	[19]
Overall	Korea	0.243	2017	[19]
Not specified	Singapore	0.450 - 0.890	2018	[23]
Not specified	Poland	0.670 - 1.110	2018	[23]
Not specified	China	0.140 - 0.260	2018	[23]
Not specified	USA	0.430	2018	[23]
Not specified	Iran	0.300	2018	[23]

After identification of the electricity demand, the next step is to determine the available RESs and to select one of them or the optimum combination of them. There are zero-energy WWTPs that utilized only biogas whereas there are also WWTPs that could meet only a little fraction of its energy demand even if employed multiple RESs in the facility (see Table 2.4).

Table 2.4. Summary of literature review on renewable energy integration

Country	Scope	RES(s)	Type of the study	Fraction of supply by RE (%)	Impact	Source
Austria	Austria WWTP	Hydraulic	In practice	~2.5		[28]
USA	Clark County WWTP	Hydraulic	In practice	>100.0	Revenue	[28]
Turkey	Gaziantep WWTP	Hydraulic	In practice	~4.0	~60k $ saving	[33]
USA	11 Water Treatment Plants and WWTPs	PV Fuel Cell Cogen.	In practice		9.5M $ 44 Mt CO_2 saving	[34]
Italy	a WWTP	Co-digestion of sludge and municipal waste	In practice	85.0		[35]
USA	EBMUD WWTP (San Francisco)	Co-digestion of sludge	In practice	130.0	3M $ revenue	[19], [28],

Country	Scope	RES(s)	Type of the study	Fraction of supply by RE (%)	Impact	Source
		and food waste				[36], [37]
Turkey	Muğla WWTP	CHP	In practice	52.0		[38]
China	WWTP (A^2O)	AD&CHP + PV	In theory	65.0		[29]
Palestine	a WWTP (CAS & AD)	Biogas burner	In practice	60.0		[39]
	a WWTP (CAS & AD)	PV	In theory	<5.0		
	a WWTP (EAAS)			9.0		
	a WWTP (MBR)			15.0		
Korea	Kiheung Respia WWTP	BIPV Hydraulic Heat Pump	In theory	~6.5		[40]
China	WWTP	EE & CHP	In theory	<50		[41]
		EE & PV		<100		
		EE & CHP & PV		>100		
sub-Saharan Africa	WWTP (CAS) without irrigation	CHP & PV & Wind	In theory	33.0-55.0		[42]
	WWTP (CAS) with irrigation			13.0		

3 DATA SOURCES AND METHODOLOGY

In this chapter, the methodology and the data sources used in the study are explained, and limitations are identified. The following four work packages were defined and planned for the study:

1. **Data Gathering:** collecting data related to
   i. WWTPs, and
   ii. other simulation program parameters such as electrical load, costs of investment, operation and maintenance (O&M), derating factor, interest rates, emission factors, *etc.*

   by using the following primary and secondary data sources and tools:

   a. Online survey preparation and dissemination
   b. Literature review (Water and Sewerage Authorities (WSA) Annual Activity Reports (AAR), Provincial Environmental Status Reports (PESR) and Inventories of Ministry of Environment and Urbanization (MoEU), academic and white papers, organizational journals, *etc.*)
   c. Personal communication via phone, mail, and fax
2. **Identification of energy intensity (EI) by type/process of the plants:** determining the energy intensities by analyzing the collected data
3. **Simulation of the selected plants:** using a simulation software called HOMER (see Section 3.2 for details), for selected representative WWTPs
4. **Assessing the total economic and environmental impacts of integration of PV and biogas to WWTPs in Turkey:** assembling the simulation results of individual simulation models

The relationship among the work packages together with the flow of the whole process is given in Figure 3.1 below. The detailed process and the data sources are explained and defined in the following sections of this chapter.

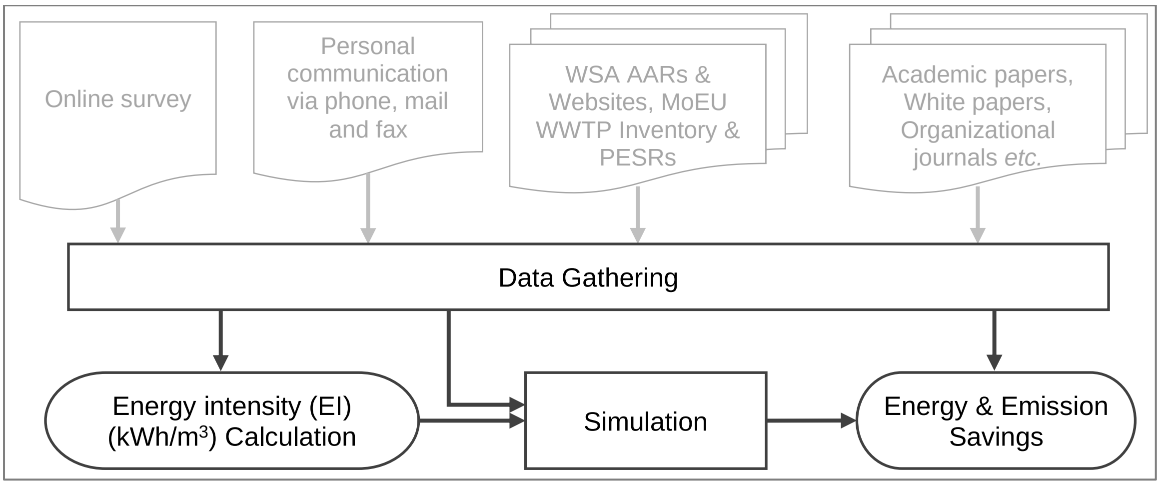


Figure 3.1. Relationship between the work packages, and the total process

3.1 Data Gathering

Data gathering is the basis of the study as is seen in Figure 3.1. The details of the data collection process are explained below. Definitions of some of the parameters are given in the footnote.

3.1.1 Data Regarding Wastewater Quality and Wastewater Treatment Plants

The amount of WW treated by type (m^3/y), number and type of WWTPs, discharged WW (m^3/y) in Turkey and city level is obtained through National Statistics on Municipal Wastewater Treatment (2016) [10]. This data is not at the plant level and does not include electricity consumption. Through an online survey, open literature, and personal communication, plant-level data for 456 WWTPs were obtained. A detailed analysis of the collected data is provided in Section 4.2.

3.1.1.1 Online Survey

An online free platform called “jotform” was used in the creation of an online survey targeting the managements of WWTPs. The survey prepared as three main parts having the following six sections (see Appendix A for the full survey):

<u>Information</u>

1. Information on Survey
2. Contact Information (3 Questions)
3. Plant Information (5 Questions)

<u>Energy Consumption</u>

4. Current and Future Energy Consumption and Energy Resource Distribution of the Plant (5 Questions)

<u>Perception of RES Integration into WWTPs</u>

5. Evaluation of Renewable Energy Sources (5 Questions)
6. Questions and Comments (Optional) (1 Question)

The type of the plant, the processes used, the number of main equipment it has and their power, amount of treated wastewater, the amount of energy consumption in total and by processes, the amount of energy generation by source, the amount of sludge and biogas produced were asked to participants including questions evaluating their perception on renewable energy resource integration to WWTPs.

In the information part, ethical approval for the questionnaire was provided (see Appendix B). The participants were also provided with contact information of both the student and the supervisor for any questions. The participants' responses were recorded online and downloaded as an excel file from jotform.

Various videos presenting the processes in the specific WWTPs and the guideline prepared by the Union of Municipalities of Turkey were used [43] to provide a detailed list of processes used in WWTPs in the related questions. The third part of the survey, namely perception, was modified for Turkey from the research led by the University of Queensland, Australia and conducted by the Water Research Foundation [44]. Following the completion of the survey preparation, various experts at different levels were also consulted besides the thesis supervisor.

As a first step, the top 12 metropolitan municipalities representing half of Turkey, in terms of the number of population were selected. In order to disseminate the survey among them, e-mail addresses and phone numbers of the related personnel in their WSAs were collected through the websites of the WSAs.

The formal letter, prepared by the Science Institution of Hacettepe University (see Appendix C) including the letter prepared by the thesis supervisor (see Appendix D), asking selected WSAs' participation in the survey was sent to the collected e-mail addresses in July 2018.

15 responses for various WWTPs were collected until December 2018. However, it was not sufficient as the total number of WWTPs of the selected WSAs is 368 according to the latest data published by Turkstat in 2016 [10]. In December 2018 and in February 2019, two reminders were sent to the WSAs which did not response previously.

At the end of the period of seven months, the total number of responses was 24 and four of them were not eligible to be taken in the evaluation as three were duplicates and one is a landfill leachate treatment plant (see Table 3.1).

Table 3.1. Summary of questionnaire dissemination and getting a response

Date of Mail Sending	Date of Response	Number of WWTPs
18.07.2018	23.07.2018	2 (1 is duplicate)
	29.08.2018	3
	06.09.2018	4 (1 is landfill leachate treatment)
	07.09.2018	1
	10.09.2018	2
	11.12.2018	3 (2 are duplicate)
05.12.2018	28.12.2018	1
25.02.2019	26.02.2019	1
	28.02.2019	1
	02.04.2019	6

3.1.1.2 Open Literature

In parallel with the survey dissemination, needed information for WWTPs of 30 metropolitan municipalities were collected from AARs of their WSAs for the year 2017 (see Table 3.2).

Table 3.2. Collected data for WWTPs

No	Data	Unit
1.	WWTP Name	N/A
2.	Data Year	Year
3.	AAR Year	Year
4.	City	N/A
5.	District	N/A
6.	Type	N/A
7.	Does it have DSWWD?	N/A
8.	Process of the WWTP	N/A
9.	Commissioning Year	Year
10.	Capacity	m^3/day
11.	Flow Rate (Amount of Treated Wastewater)	m^3/year
12.	Population Served	capita
13.	AKM	mg/l
14.	COD	mg/l
15.	BOD	mg/l or kg/year
16.	Electricity Consumption	kWh/year
17.	Electricity (Biogas) Production	kWh/year
18.	Electricity (other) Production	kWh/year
19.	Electricity Consumption from Grid	kWh/year
20.	Natural Gas Consumption	Nm^3/year

No	Data	Unit
21.	Biogas Production	m^3/year
22.	Dried Sludge	kg/year
23.	Total Solid Waste	kg/year
24.	Sludge	kg/year
25.	Operating Cost	TL/year
26.	Electricity Cost	TL/year

As some of the AARs do not have all the information needed, websites of WASs, PESR of MoEU (2017), and WWTP Inventory (2018) of MoEU were used to complete data gaps. They were also used to validate the collected AAR data especially time-independent ones such as capacity, commissioning date and type of the plant as well as the process used in the plant.

3.1.1.3 Personal Communication

Following the completion of data collection from literature, only the main missing data as one of the followings were identified to be asked for:

- energy consumption and generation,
- amount of treated wastewater,
- used process in the plant,
- type of the plant,
- amount of generated sludge and biogas.

Related departments of WSAs were contacted through phone, and the list of needed data had sent them via fax/e-mail. Their responses collected via phone/e-mail.

3.1.2 Data Regarding Simulation Program

For identification of the optimum combination of RES that will be used in the WWTPs, Hybrid Optimization Models for Energy Resources (HOMER) software was used. HOMER software is a simulation program developed by the National Renewable Energy Laboratory (NREL) that optimizes the hourly performance of various system components for minimum net present cost based on pre-defined technical constraints and parameters. HOMER’s output does not give only one optimum solution. It provides results for all the combinations to allow the user to compare the results. It also allows exercising sensitivity analysis [45], in which different figures for different parameters such as electricity selling price, emission penalty, *etc.* are also simulated.

In order to run the simulation, other parameters, in addition to WWTP data, were needed to be entered the program:

1. Biogas related data
2. Photovoltaic (PV) system related data
3. Grid related data
4. Economics related data
5. Emission penalties related data

3.1.2.1 Data Regarding Biogas Power

In HOMER, electricity generation from biogas is simulated via a generator component that uses biogas as a fuel that is produced from a biomass resource. In WWTPs' case, the biomass resource is the wastewater sludge.

Biomass Resource

It is possible to insert a monthly amount of a biomass resource into the system to produce the needed biogas in HOMER software. Sludge production of 212 WWTPs was already obtained from primary and secondary sources by data collection (see Section 3.1.1). However, it was found out that some of them were reported as the final amount of sludge as waste, not as the amount of raw sludge digested to produce biogas. Therefore, sludge production yield per capita was obtained from the literature research (see Table 3.3) as population data of 343 WWTPs are available. Based on literature research, the sludge production yield was assumed to be 43.5 g/day.capita as the middle value of the average and the median.

Table 3.3. Sludge production yield in the ltierature (g/day.capita)

Sludge Production (g/day.capita)	Year	Source
40 – 60	2009	[38]
80	2007	[46]
23 – 47 (for Turkey)	2010	[47]
50 (for İstanbul WSA)	2014	[47]

Average value for Turkey: 40
Median value for Turkey: 47

The amount of raw sludge produced was calculated by using equation 3.1.

$$RS = SPY * PE \quad (3.1)$$

Where RS (kg/y) is the annual amount of produced raw sludge, SPY (kg/y.capita) is the raw sludge production yield (43.5*0.365 kg/y.capita), and PE (capita) is the amount of population served of the WWTP.

For this thesis, it was assumed that the biogas is generated by anaerobic digester process because it is the most mature, therefore economic method for WWTPs especially for the ones in Turkey [48], [49] (see Figure 3.2). However, it is not possible to add a component representing the AD for the biomass/biogas conversion process while the conversion of the available biomass to biogas is calculated by the Gasification Ratio (kg biogas/kg biomass) parameter of the biomass resource. In this case, the cost of the investment of anaerobic digester was included in the cost of the generator component as a system building cost.

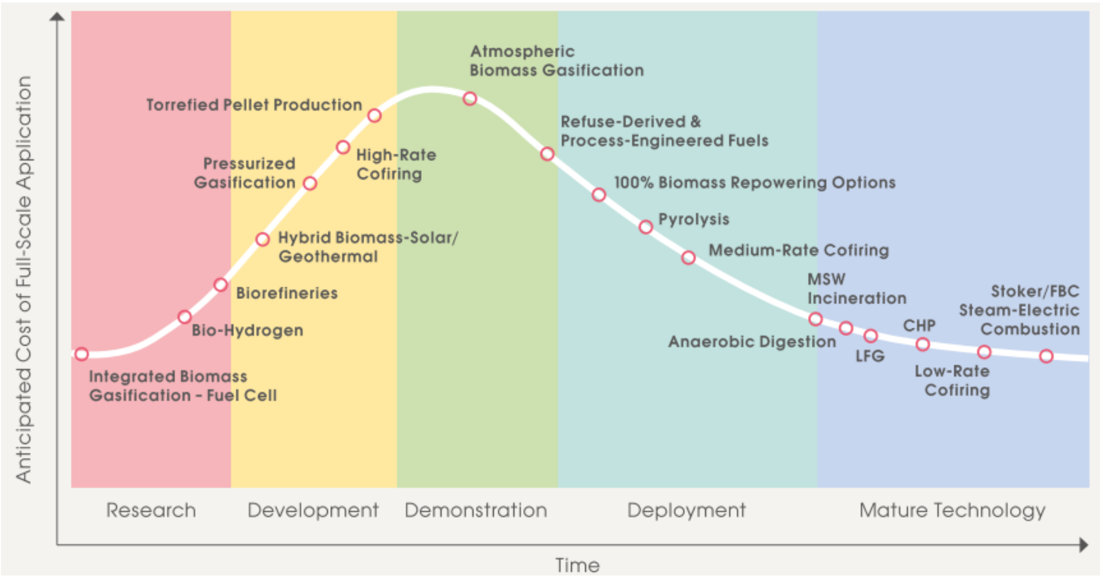


Figure 3.2. Maturity status of biomass power technologies [49]

Because in the WWTPs, the available biomass, sludge, in other words, is already produced as a result of the treatment process without creating an additional cost, the biomass price parameter ($/ton) assumed to be the variable O&M cost of the anaerobic digester. Literature research was conducted for this purpose. It was concluded that the O&M cost of the digesters has very wide ranges and the units of the available data were hard to be converted into $/ton. The obtained data in the literature was converted into as similar units as possible and presented in Table 3.4. The converted version of the data given in IRENA's Report [49] was used (third row of Table 3.4) as 22.1 $/ton for the biomass price.

Table 3.4. O&M cost of an anaerobic digester in literature

O&M Cost	Unit	Data Year	Source
750-1,000	$/kW	2007	[50]
328 – 581	$/m^3 digester volume	2009	[51]
22.1	$/t sludge	2010	[49]
0.0169 – 0.0463	$/m^3 plant size	2011	[52]

Another parameter of biomass that should be given to the HOMER software is the carbon content of the biomass resource. The figure was obtained from the literature. In the HOMER software [53], it is indicated that a typical value for carbon content is 50% for a biomass resource however it is usually valid for wood and food sources which are purer than wastewater sludge. The range found in the literature is from 19% to 50% (see Table 3.5) with a median of 34% and an average of 36%. As a result, the carbon content of the biomass was chosen as 35%.

Table 3.5. Carbon & sulfur content of biomass resource (WW Sludge) in literature

Carbon Content (% of mass)	Data Year	Source
35	2010	[54]
33	2011	[55]
33 – 50	2013	[56]
19 – 29	2015	[57]
37	2018	[58]
50	2019	[53]

Average: 36% of the mass
Median: 34% of the mass

As indicated earlier, the amount of biogas that will be produced from biomass resource was calculated by the HOMER via using the gasification ratio (kg biogas/kg biomass) parameter of the biomass resource. However, as was noted above, it was assumed that the biogas is generated by the anaerobic digestion process. Thus, the gasification ratio was used for the anaerobic digestion process instead of the gasification process itself. Therefore, the gasification ratio was decided accordingly.

In the literature, there are several biogas yields based on different parameters such as per kg volatile solids (VS) removed, per kg sludge, *etc.* (see Table 3.6).

Table 3.6. Biogas production yield in literature

Biogas Yield	Unit	Data Year	Source
0.500 – 0.750	m^3/kg VS	2015	[47]
0.750 – 1.120	m^3/kg VS removed		
0.030 – 0.040	m^3/d-capita		
0.800 – 1.100	m^3/kg VS removed	N/A	[59]
0.015 – 0.022	m^3/d-capita (pre treatment)	2000	[60]
0.028	m^3/d-capita (secondary treatment)		
0.800 – 1.200	m^3/kg VS removed	2012	[48]
0.300	m^3/kg TS	2008	[61]
0.150	m^3/kg wet weight		
0.300 – 0.700	m^3/kg VS	2012	[62]
0.300	m^3/kg VS	2011	[54]
0.015 – 0.022	m^3/d-capita	2010	[63]
0.380 – 0.800	m^3/kg sludge		
0.017 – 0.140	m^3/kg sludge	2008	[64]

The values from the literature do not match with the collected data. Therefore, it was calculated based on the available data. The correlation between biogas (m^3/y) and the BOD (kg/y) values of 19 WWTPs in 2016 and 2017 is 89% (see Figure 3.3) as Brandoni and Bosnjakovi [42] also used the relationship between COD and biogas production.

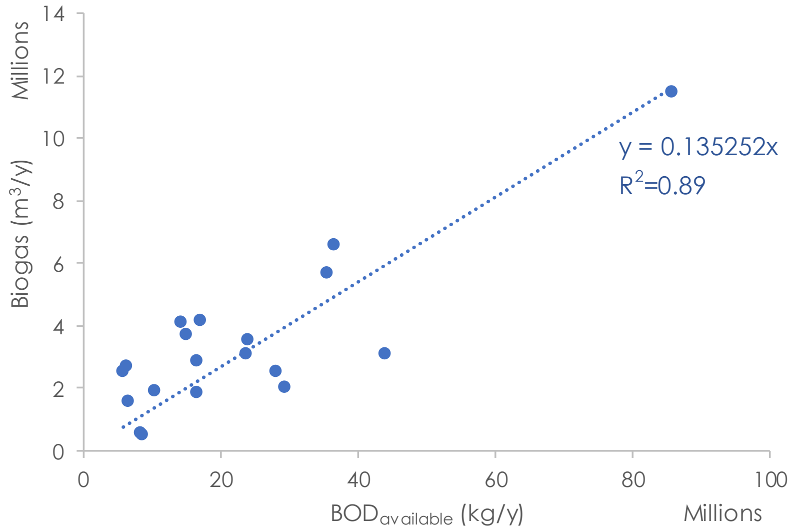


Figure 3.3. Biogas and BOD correlation of collected data from 2016 and 2017

According to the relation between biogas production and BOD, biogas production was calculated with the equation 3.2, where BG (m^3/y) is the annual biogas production, BOD_{input} (kg/y) is the annual BOD value of the influent:

$$BG = 0.135252 * BOD_{input} \tag{3.2}$$

To find the gasification ratio for the WWTPs which do not have the BOD_{input} data, an equation depending on PE was used based on PE data availability (see Table 3.7).

Table 3.7. Availability of the BOD_{input} (mg/l) and population served (PE) data

		BOD_{input} Data		
		Exist	Not exist	Total
PE Data	Exist	48	**295** *(calculated)*	343
	Not exist	9	104	113
	Total	**57**	399	456

According to the wastewater and pollution generation table (called Tablo 2.1) in the Communiqué on Technical Procedures for Wastewater Treatment Plants [65], PE depended BOD values are given (see Table 3.8). For the WWTPs of which PE is less than 2,000 or more than 100,000 people, it was assumed that the BOD value is the same with the minimum and maximum values respectively in the table.

Table 3.8. BOD (kg/day.PE) based on population served (adapted from [65])

Population	BOD_{input} (kg/day.PE)
2,000 – 10,000	0.040
10,000 – 50,000	0.045
50,000 – 100,000	0.050

The BOD_{input} values of 295 WWTPs were calculated through equation 3.3 where BOD_{input} (kg/y) is the annual BOD value of the influent, PE (capita) is the number of people served by the WWTP, BOD_{capita} (kg/y.capita) is the annual per capita BOD value of the influent which is decided based on population.

$$BOD_{input} = PE * \mathrm{BOD}_{capita} \tag{3.3}$$

The gasification ratio was calculated with equation 3.4 where φ_g (kg/kg) is the plant-specific gasification ratio (kg biogas/kg biomass), BG (m^3/y) is the biogas production of WWTP given/calculated with equation 3.2, RS (kg/y) is the raw sludge production in the WWTP calculated with equation 3.1 and 1.2 (kg/m^3) is the density of biogas.

$$\varphi_g = \frac{\mathrm{BG} * 1.2}{RS} \tag{3.4}$$

Biogas Fuel

For the characteristics of the biogas fuel such as density (kg/m^3) and Lower Heating Value (LHV) (MJ/kg), academic and white papers were used. The density of the biogas produced from sewage sludge was assumed to be 1.2 kg/m^3 as a result of the literature research (see Table 3.9).

Table 3.9. The density of biogas in literature

Density (kg/m^3)	Data Year	Source
1.150	2009	[66]
1.201	2010	[67]
1.100	2011	[68]
1.246	2018	[46]
1.211	2019	[69]

Average: 1.182 kg/m^3
Median: 1.201 kg/m^3

Lower Heating Value (LHV) of biogas was chosen as 19 MJ/kg based on the average of the mean and median values of the figures found in the literature research (see Table 3.10).

Table 3.10. The lower heating value (LHV) of biogas in literature

LHV (MJ/m^3)	LHV (MJ/kg)*	Data Year	Source
24.5 – 27.6	20.4 – 23.0	2009	[66]
22.3	18.6	2010	[67]
22.4	18.7	2011	[60]
21.0	17.5	2011	[68]
15.9 – 27.8	13.3 – 23.2	2012	[48]

*Density is assumed to be 1.2 (kg/m^3) as indicated earlier
Average (MJ/kg): 19.2 MJ/kg
Median (MJ/kg): 18.7 MJ/kg

Generator

It was assumed that the selected generator is capable of producing electricity by using the biogas produced in the WWTP. According to IRENA's Report called Renewable Power Generation Costs in 2018 [70] the total investment cost of bioenergy is 2,100 $/kW in 2018, decreasing from 2,700-2,850 $/kW in 2017 (see Figure 3.4).

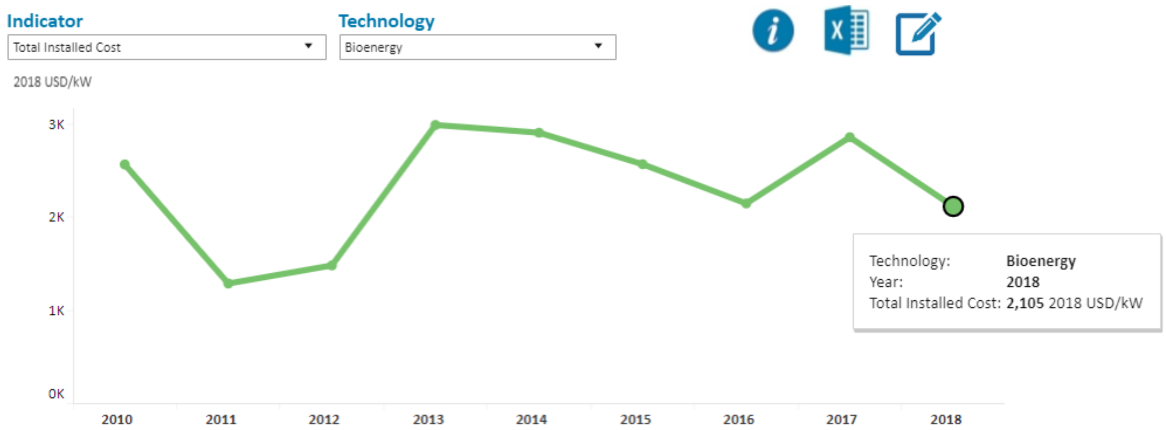


Figure 3.4. Annual change of total investment cost of bioenergy (2010-2018) [71]

For the initial capital cost and O&M cost of the generator, data is obtained from the market, sectoral reports and academic papers (see Table 3.11). By taking the median value of the figures in the literature the initial capital cost was assumed as 2,000 $/kW and the O&M cost was assumed to be 0.015 $/kW-h.

Table 3.11. Initial investment and O&M costs of a generator in literature

Investment Cost ($/kW)	O&M Cost ($/kW-h)	Data Year	Source
1,500 – 2,500*	0.015	2009	[51]
1,650 – 3,665		2011	[72]
2,000 – 3,000	0.012	2011	[73]
420*		2013	[74]
3,508		2014	[75]
7,220		2015	[76]
1,000 – 1,300*		2017	[77]
1,500*	0.021	2017	[42]
956 – 2,920		2018	[46]
2,105		2018	[71]
Average: 2,350 $/kW Median: 2,000 $/kW	Average: 0.016 $/kW-h Median: 0.015 $/kW-h	* Only CHP/motor cost	

The replacement cost ($/kW) of the generator was assumed to be the same as the investment cost. The lifetime of the generator was decided as 60,000 hours [42], [77]. The fuel consumption rate of the generator is used as it is in the HOMER software.

Emissions data of CO (g/kg fuel), unburned HC (g/kg fuel), particulate matter (g/kg fuel), fuel sulfur to PM (%), and NO_x (g/kg fuel) required in the HOMER software for the simulation of emissions from electricity generation from biogas were decided based on literature. Fuel Sulfur to PM was assumed to be 0 as it was assumed that desulfurization is applied to the biogas because the sulfur has a corrosive effect on the equipment. The rest of the emissions achieved in the literature are presented in Table 3.12 and they are assumed to be the middle value between their average and the median.

Table 3.12. Emissions from biogas generator in literature

CO (kg/kg)	Unburned HC (kg/kg)	PM (kg/kg)	NO_x (kg/kg)	Data Year	Source
5.2	4.8	0.00029	10.3	2004	[78]
4.9 – 5.9			3.8 – 10.3	2008	[79]
9.1			3.6	2014	[80]
14.9 – 15.8	2.5 – 2.9		4.2 – 4.6	2016	[81]
Average: 9.3 kg/kg Median: 7.5 kg/kg	Average: 3.4 kg/kg Median: 2.9 kg/kg		Average: 6.1 kg/kg Median: 4.4 kg/kg		

Summary of Data Regarding Biogas Power

The parameters related to power generation from biogas, their units, value range found in the sources and the sources themselves as well as the used value in the software are shown in Table 3.13.

Table 3.13. Used values for biogas power related data

	Data	Unit	Range	Source	Used Value
Biomass Resource	Available Amount (Sludge production in individual WWTPs)	ton/day	N/A	Field Data	PS[a]
	Average Price	$/ton	22.1	[49]	22.1
	Carbon Content	% of mass	19 - 50	[53]–[58]	35
	Gasification Ratio (biogas to biomass)	kg/kg	N/A	Field Data	PS[a]

	Data	Unit	Range	Source	Used Value
Biogas Fuel	Density	kg/m^3	1.10 - 1.25	[46], [66]–[69]	1.2[b]
	Lower Heating Value (LHV)	MJ/kg	13.3 – 23.2	[48], [60], [66]–[68]	19[b]
Generator	Initial Capital of generator	$/kW	420 – 7,220	[42], [46], [51], [71]–[77]	2,000
	Replacement Cost of generator	$/kW	N/A	Assumption	2,000
	Cost of O&M of generator	$/kW-op.h.	0.012-0.021	[42], [51], [73]	0.015
	Lifetime	k hours	48 – 60	[42], [77]	60
	Fuel Consumption	kg/kWh	N/A	HS[c]	0.014[d] 0.244[e]
	CO	g/kg fuel	4.9 – 15.8	[78]–[81]	8
	Unburned HC	g/kg fuel	2.5 – 4.8	[78], [81]	3.2
	Particulate Matter	g/kg fuel	0.00029	[78]	0.00029
	Fuel Sulfur to PM	%	N/A	Assumption	0
	NO_x	g/kg fuel	3.6 – 10.3	[78]–[81]	5.5

[a] Plant Specific
[b] These values were used in the conversion of some parameters given with various units in the literature.
[c] Homer Software
[d] Intercept coefficient of the fuel-power curve
[e] Slope of the fuel-power curve

3.1.2.2 Data Regarding Photovoltaic System

In HOMER software (see Section 3.2 for more details), electricity generation from a photovoltaic system is simulated via a photovoltaic panel component that uses solar radiation as a resource and an inverter for the conversion of the generated electricity from DC to AC.

Solar Resource

For solar resource data, mainly secondary data sources were used. HOMER software has the ability to provide local data for local solar irradiation (GHI) (kWh/m^2-day), clearness index (%) and temperature (°C) for a specified location. Therefore, the locations of the WWTPs were provided to the system if it was available in the database. If it not available, the districts in which the WWTP located were used as locations.

The locations of the WWTPs were collected from the AARs and websites of WSAs, PESRs and WWTPs Inventory of MoEU. When no information was reached via these sources, GoogleMaps was used as a last alternative.

Photovoltaic Panels

Costs of investment ($/kW) including mounting *etc.*, replacement ($/kW), and O&M ($/y-kW) were obtained from literature such as sectoral reports, academic papers, *etc.* The initial capital cost ($/kW) of PV is keeping the track of decreasing since 2010 [71] thanks to economies of scale besides technological developments (see Figure 3.5).

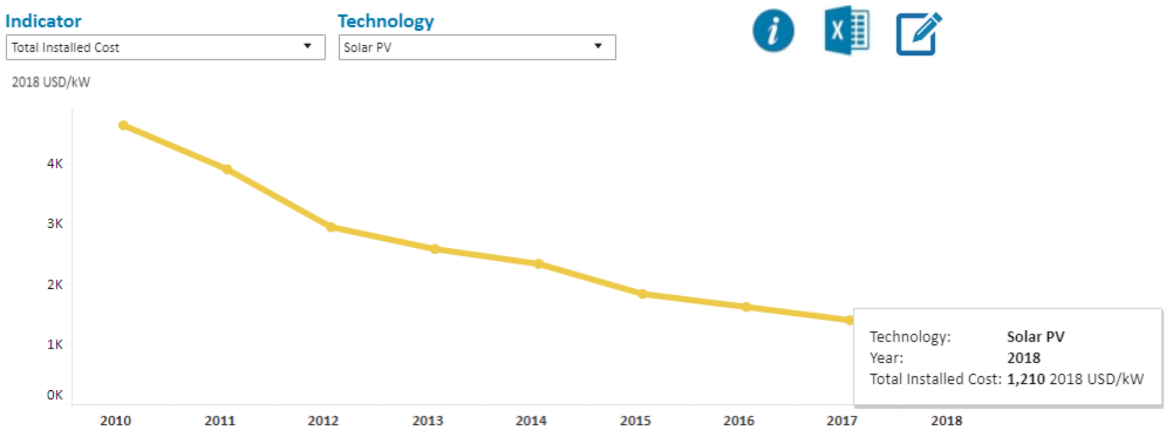


Figure 3.5. Annual change of total investment cost of PV (2010-2018) [71]

Literature research also indicates a decline in the total cost of investment. Table 3.14 represents various initial cost values in distinct years found in different sources. Considering especially the last two years (the reports of EÜD [82], IRENA [70], and the database of IRENA [71]) and the fast decrease in the investment costs, the initial investment cost of PV for Turkey was assumed to be 1,100 $/kW.

Table 3.14. Initial investment cost of PV in literature

Investment Cost of PV ($/kW)	Data Year	Source
7,000	2009	[83]
5,217	2010	[84]
5,000	2010	[85]
2,210	2011	[86]
2,500	2011	[87]
2,840	2011	[88]
1,131 – 1,716	2014	[89]
1,330 – 1,883	2014	[90]
1,388	2017	[71]
1,500	2017	[42]
900	2018	[82]
1,200*	2018	[70]

Investment Cost of PV ($/kW)	Data Year	Source
1,210	2018	[71]
959 – 3,500	2018	[38]

*The figure includes inverter cost for Turkey. It can be assumed ~1,150 $/kW without an inverter.
Average (2017-2018 without extreme point): 1,189 $/kW
Median (2017-2018 without extreme point): 1,200 $/kW

The share of the operation and maintenance (O&M) cost in the total investment cost was so low while the cost of the PV system was higher. With the decline in total system cost, the share of the O&M has increased to about 20-25% in some countries [91] as the cost of O&M remains stable (see Table 3.15). Based on the literature review, 12 $/kW-y was chosen, and the O&M cost of the inverter also included in this value because the cost is not only for the PV modules but for all the related components.

Table 3.15. O&M cost of PV in literature

O&M Cost of PV ($/kW-y)	Data Year	Source
10	2009	[87]
13	2015	[89]
10 – 45	2015	[92]
10 – 19	2015	[70]
10 – 18	2015	[91]
13	2017	[93]

Average (without extreme point): 13 $/kW-y
Median (without extreme point): 12 $/kW-y

Since the project lifetime was assumed to be 25 years, the PV modules replacement cost was assumed to be zero (0) as their lifetime is also 25 years. This approach was also used in the study of Özkök and Güler [89] and the thesis of Telli [85].

Temperature Coefficient of Power (%/^{o}C), NOCT (^{o}C), and efficiency (%) at STC are usually given by the PV module producers. Based on online market research, it was identified that the value of Temperature Coefficient of Power changes between 0.37 and 0.47 %/^{o}C while NOCT changes between 43 – 47 ^{o}C. Efficiency varies between 15.7%–19.6%. To represent an average for these parameters, the polycrystalline solar module coded JMK275-60 in the HOMER Software was chosen. The derating factor is 88% for this PV array in the HOMER, while the ground reflectance (albedo) is 20%.

It was assumed that WWTPs will not use a tracking system for their PV panels. Since Turkey is on the northern hemisphere, the azimuth angle will be 0° in order to be faced to the equator. HOMER will assign the slope of the PV panel based on the latitude value of the assigned location of the WWTP.

It was assumed that the WWTPs own a suitable land for the PV installation, so the cost of the land use was not included separately to the cost calculations.

Inverter

Based on the selected PV module, the HOMER software defined an inverter of Studer called Xtender XTH 3000-12 with 10 years of lifetime, 93% of input and rectifier efficiencies, and 100% of relative capacity. For the cost of investment ($/kW), a wide range of figures was obtained from various sources (see Table 3.16).

Table 3.16. Initial investment cost of inverter in literature

Investment Cost of Inverter ($/kW)	Data Year	Source
313.3	2006	[94]
700.0	2009	[83]
1,000.0	2010	[85]
500.0	2010	[72]
741.0	2011	[88]
470.0	2014	[89]
300.0	2017	[42]
41.3 - 144.3	2017	[91]
68.7	2018	[70]

Average (2017-2018): 139 $/kW
Median (2017-2018): 107 $/kW

According to the data used in the latest report of IRENA [70], inverter costs in Turkey are relatively lower than the other countries (see Figure 3.6). Based on the literature review, investment cost was assumed to be 110 $/kW. Replacement cost was assumed to be the same with the investment cost like the approach used in Thesis of Telli [85]. The O&M cost of the inverter was assumed to be included in the cost of O&M of the PV system. Thus, it was assumed to be zero (0).

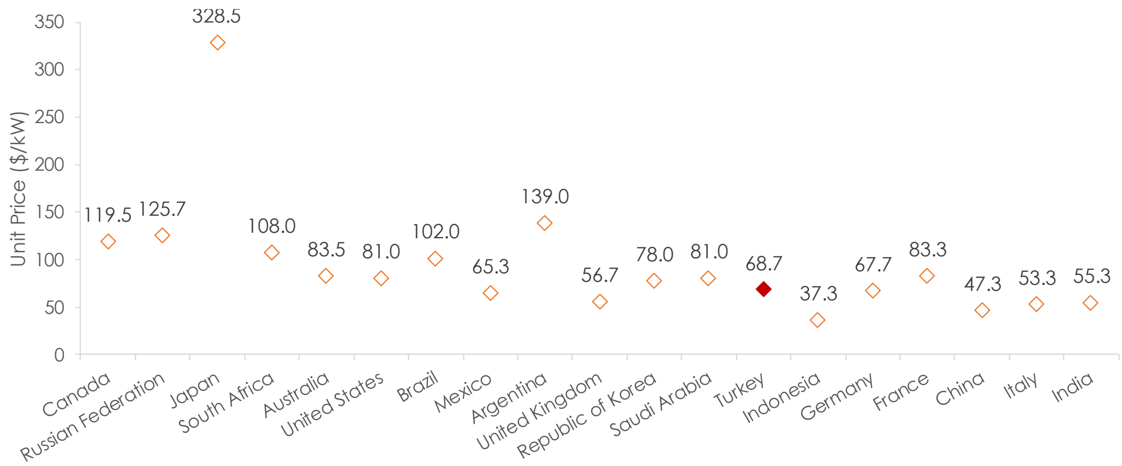


Figure 3.6. Inverter cost in different countries ($/kW) (adapted from [70])

Summary of Data Regarding Photovoltaic System

Table 3.17 below presents the parameters related to solar power generation together with their units, value range found in the sources and the sources as well as the used value in the software.

Table 3.17. Used values for photovoltaic system related data

	Data*	Unit	Range	Source	Used Value
Solar Resource	Local solar radiation (GHI)	kWh/m^2-day	N/A	HS[a]	PS[b]
	Clearness Index	%	N/A	HS[a]	PS[b]
	Temperature	ºC	N/A	HS[a]	PS[b]
	Location (District of the WWTP)	N/A	N/A	Field Data	the
Photovoltaic Panels	Investment Cost of PV system	$/kW	900 - 1,500	[38], [42], [88]–[90], [70], [71], [82]–[87]	1,100
	Replacement Cost of PV system	$/kW	0	[85], [89]	0
	Cost of O&M of PV system	$/y-kW	10.0 - 19	[70], [87], [89], [91]–[93]	12
	Lifetime	years	25	MR[c], HS[a]	25
	Derating Factor	%	N/A	HS[a]	88
	Ground Reflectance (albedo)	%	N/A	HS[a]	20
	Temperature Coefficient of Power	%/ ºC	-0.37- - 0.47	MR[c], HS[a]	-0.41
	NOCT	ºC	43 - 47	MR[c], HS[a]	45
	Efficiency at STC	%	15.7 - 19.6	MR[c], HS[a]	16.8
	Azimuth Angle	º	0 - 180	HS[a]	0
	Slope Angle	º	~	HS[a]	PS[b]
Inv ert	Investment Cost of Inverter	$/kW	37.3 – 1,000.0	[42], [70], [72], [83],	110

Data*	Unit	Range	Source	Used Value
			[85], [88], [89], [91], [94]	
Replacement Cost of Inverter	$/y	N/A	Assumption	110
Cost of O&M of Inverter	$/y-kW	N/A	Assumption	0
Input Lifetime	years	N/A	HS[a]	10
Input Efficiency	%	N/A	HS[a]	93
Rectifier Relative Capacity	%	N/A	HS[a]	100
Rectifier Efficiency	%	N/A	HS[a]	93

*Some of the terms are defined at the beginning of Section3.1.
[a] HOMER Software
[b] Plant Specific
[c] Market Research

3.1.2.3 Data Regarding Grid

Since WWTPs are grid-connected, HOMER Software needs the prices ($/kWh) for purchasing electricity from the grid and selling the surplus electricity to the grid. It also requires the grid emission data to calculate the emissions caused by the electricity purchased from the grid and to compare the environmental impacts of the scenarios.

Electricity Selling and Buying Price

Energy Market Regulatory Authority (EMRA) quarterly publishes the tariffs of electricity purchasing prices for the end-users [95]. The low voltage electricity purchasing price for industrial users is 0.4974 TL/kWh excluded the taxes and additional costs (0.0849 $/kWh for the exchange rate of 5.86 in May 2019). To find the tax included purchasing price, available data were used. In the collected data of WWTPs, the total annual electricity cost is available for 12 WWTPs in 2016 and 7 WWTPs in 2017. By using the exchange rates in the respective years [32], it was found that the unit prices vary between 0.0610 and 0.1253 $/kWh (see Figure 3.7).

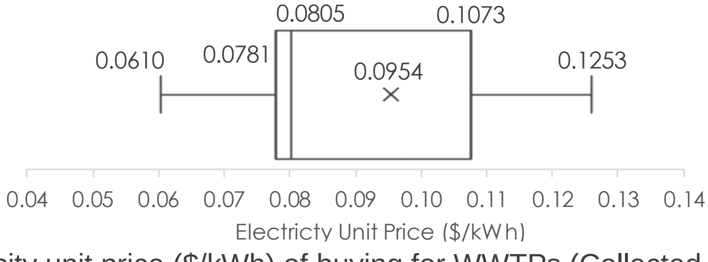


Figure 3.7. Electricity unit price ($/kWh) of buying for WWTPs (Collected Data)

By considering the following two issues, the unit price was selected as 0.080 $/kWh;

i- The price published by EMRA excludes taxes, funds, and payments,

ii- The opportunity of WWTPs to get a discount on the electricity prices,

The feed-in-tariff price in the related Law was used [96] for the electricity selling price. It is 13.3 $ cent/kWh and the same for solar energy and bioenergy. Additional incentives given for domestic equipment utilization was not included in the study. The cases of no selling and a lower selling price (5 $ cent/kWh) were also simulated.

Grid Emissions

HOMER software allows the user to input other air emissions besides GHGs. Total gas emission of the grid was calculated by using the following equation 3.5, where GEF_{gas} (kg CO_2/MWh) is the grid emission factor for the specific gas per MWh generated, EF_{fuel} (kg CO_2/MWh) is the fuel-specific emission factor of the specific gas, FS (%) is the share of the fuel in total electricity generation in 2017.

$$GEF_{gas} = \sum EF_{fuel} * FS_{fuel} \tag{3.5}$$

Electricity generation by supply is taken from TEİAŞ [97] (see Table 3.18). EF_{fuel} for CO_2 is taken from the study of Arı and Aydınalp [98] as it is based on Turkey. Because of a lack of information in the literature, the life cycle analysis study on electricity generation completed by Atılgan and Azapagic [99] was taken as the basis for the selection of other air emission factors (see Table 3.18).

Table 3.18. Fuel specific air emission factors (EF) (kg CO_2/MWh) of Turkey [98], [99] and fuel shares in electricity generation (FS) (%) in Turkey in 2017 [97]

	NG	Fuel Oil	Lignite	Hard Coal	Source
FS (%)	37.2	0.4	13.7	19.1	[97]
EF (kg CO_2/MWh)	374	755	1,080	1,018	[98]
EF (kg CO/MWh)	0.27		0.67	0.23	[99]
EF (kg PM/MWh)	0.003		1.16	0.33	[99]
EF (kg SO_2/MWh)	0.003		7.84	3.88	[99]
EF (kg NO_x/MWh)	0.41		2.11	0.65	[99]

The calculated emission factors and the default figures in the HOMER Software are compared in Table 3.19.

Table 3.19. Grid emission factors calculated and default values in the HOMER software

	Emission Factor (g/kWh) (calculated)	**Emission Factor** (g/kWh) HS[a]
CO_2	482.80	499.87
CO	0.24	0.00
UHC[b]	N/A	0.00
PM	0.22	0.00
SO_2	1.82	2.74
NO_x	0.57	1.34

[a] HOMER Software
[b] Unburned Hydrocarbons

As can be clearly seen in the table, the default values of HOMER do not represent Turkey. Thus, calculated EFs were used for the simulation of the WWTPs.

Summary of Data Regarding Grid

The parameters related grid connection, their units, value range found in the sources and the sources as well as the used value in the software are shown in Table 3.20.

Table 3.20. Used values for grid-related data

	Data	Unit	Range	Source	Used Value
Grid	Grid Power Price	$/kWh	0.0647 - 0.0849	[95], Field Data	0.080
	Grid Sellback Price	$/kWh	N/A	[96]	0.133 & 0.050 & 0
	CO_2	g/kWh	482.80 - 499.87	[98], HS[a]	482.80
	CO	g/kWh	0.00 - 0.24	[97], HS[a]	0.24
	Unburned HC	g/kWh	0.00	HS[a]	0.00
	Particulate Matter	g/kWh	0.00 - 0.22	[97], HS[a]	0.22
	SO_2	g/kWh	1.82 - 2.74	[97], HS[a]	1.82
	NO_x	g/kWh	0.57 - 1.34	[97], HS[a]	0.57

[a] Homer Software

3.1.2.4 Data Regarding Economic Parameters

HOMER Software uses nominal discount rate (%) and expected inflation rate (%) to find the real discount rate and calculate the Net Present Value (NPV) of the system to compare the scenarios and reveal the optimal solution.

Rates of nominal discount and expected inflation were directly taken from the Central Bank of the Republic of Turkey. Since the nominal discount rate is policy rate which is also equal to the one-week repo rate [100], 24% as of 14.09.2018 [101] was used for the nominal discount rate.

The inflation rate in 2018 ranged from 10.23% to 25.24%, while the annual inflation rate was 20.3%, and decreased to 19.7% in the first quarter of 2019 [102]. It might be expected to fall during 2020, however monetary and international policies, as well as re-election in İstanbul, creates uncertainty and instability for international Credit Rating Agencies [103]. That is why, the expected inflation rate was assumed to be 20%, taking the average of the rate in 2018 and in the first quarter of 2019.

Project lifetime (years) and capacity shortage penalty ($/kWh) were assumed to be 25 years and zero (0) respectively as the default figures given by the HOMER. It was assumed that the system does not have a fixed capital cost ($) or fixed system O&M cost ($/y).

Summary of Data Regarding Economic Parameters

The parameters related to economic calculation, their units, value range found in the sources and the sources as well as the used value in the software are shown in Table 3.21.

Table 3.21. Used values for economic calculation related data

	Data	Unit	Range	Source	Used Value
Economics	Nominal discount rate	%	N/A	[101]	24
	Expected inflation rate	%	19.7 - 20.3	[102], [103]	20
	Project Lifetime	years	N/A	HS[a]	25
	System fixed capital cost	$	N/A	Assumption	0
	System fixed O&M cost	$/y	N/A	Assumption	0
	Capacity Shortage Penalty	$/kWh	N/A	HS[a]	0

[a] Homer Software

3.1.2.5 Data Regarding Emission Penalties

For countries, for instance in EU, electricity generation plant operators having more than 20 MW of thermal power are subjected to “Emission Trading System” in which the operators should pay a fine for each ton of CO_2e that exceeds their allowances or they should buy CO_2e from the market as much as the amount of their excess emissions. Or some countries directly apply a carbon tax to the carbon emitter sectors, especially manufacturing and electricity generation. The prices applied in different countries for the carbon tax and ETS (\$/ton CO_2e) are represented in Figure 3.8 according to the World Bank Carbon Pricing Dashboard [104].

The HOMER delivers an economic comparison of environmental impacts by counting this penalty fee for the related emissions. But even there are external impacts on society, such as health, comfort, *etc.*, and the environment due to CO_2e emissions, there is no such system in Turkey that makes the operators pay for their GHG emissions. Still, a penalty (\$/ton) for CO_2e was evaluated within the scope of this study on a scenario basis, to reveal the economic impact of such a system. Based on Figure 3.8, 16 \$/ton was chosen as the penalty. No air emissions penalties (CO, unburned HC, particulate matter, and NO_x) were assumed.

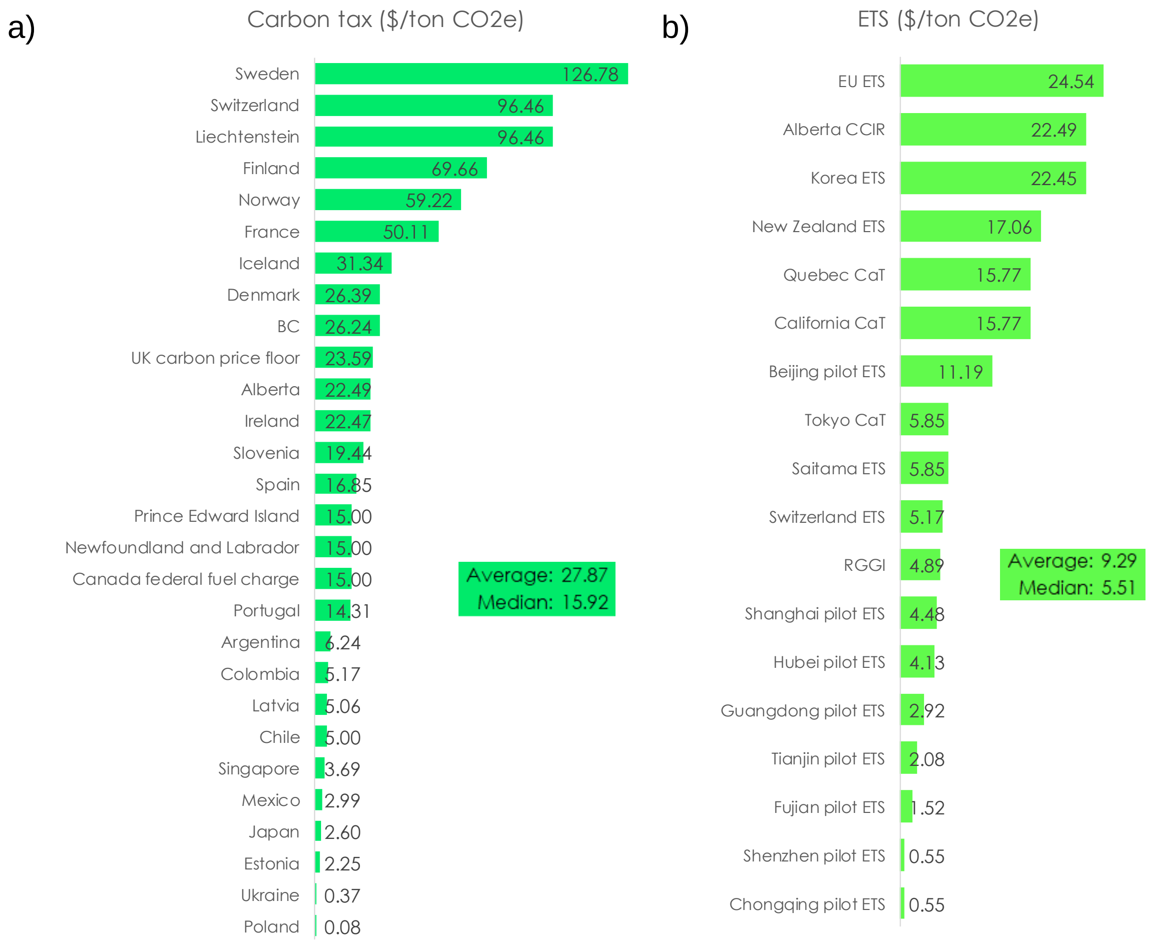


Figure 3.8. In 2019 Carbon prices in a) carbon tax system b) EU ETS (adapted from [104])

Summary of Data Regarding Emission Penalties

Table 3.22 shows the parameters related emission, their units, value range found in the sources and the sources as well as the used value in the software.

Table 3.22. Used values for emission penalties

	Data	Unit	Range	Source	Used Value
Emission Penalties	CO_2	$/ton	0.08 – 126.78	[104]	0 & 16
	CO	$/ton	N/A	Assumption	0
	Unburned HC	$/ton	N/A	Assumption	0
	Particulate Matter	$/ton	N/A	Assumption	0
	SO_2	$/ton	N/A	Assumption	0
	NO_x	$/ton	N/A	Assumption	0

3.2 Energy Intensity Calculation

To let HOMER simulate the WWTP system, it needs the electricity consumption of the WWTP. 53% of the collected 456 data includes both the electricity consumption and the amount of treated wastewater (flow rate) in the plant (240 of 456 WWTPs). For 165 WWTPs, electricity consumption was calculated by using the energy intensity (kWh/m^3) of 240 WWTPs (see Table 3.23).

Table 3.23. Availability of the electricity consumption and treated wastewater data

		Electricity Consumption		
		Exist	Not exist	Total
Treated WW Data	Exist	240	165 *(calculated)*	405
	Not exist	3	48	51
	Total	243	213	456

The energy intensities of 240 WWTPs were calculated with following equation 3.6 where EI (kWh/m^3) is the energy intensity, TWW (m^3/y) is the amount of treated wastewater, EC (kWh/y) is the annual energy consumption of the WWTP.

$$EI = \frac{EC}{TWW} \tag{3.6}$$

Outliers in the data set were defined by using Median Absolute Deviation and excluded from the energy intensity analysis (see Section 4.3 for details).

3.2.1.1 Process Categorization of the WWTPs

WWTPs use various processes to treat wastewater due to the wastewater quality, equipment features, economic concerns, discharging environment, *etc.* even though their type (primary, secondary, tertiary) are the same. To ensure a rational benchmarking of EIs among WWTPs, some of the processes were assumed to be in the same categories. The categories based on the processes used in the plants are given in Table 3.24. In the case of a WWTP with an unknown type, it was identified based on the process. If its process was known as one of the secondary treatments, additionally includes nitrogen and/or phosphorus removal, then it was labeled as tertiary (advanced) treatment.

Table 3.24. Categorization of wastewater treatment plants based on their processes

Type	Process Used*	Category
Primary	Infiltration	Natural
Primary	Pre-Treatment	Natural
Primary	Pre-Treatment + DSWWD	Natural
Primary	Natural Treatment	Natural
Primary	Slow Sand Filtration	Natural
Secondary	Stabilization Pond	Natural
Secondary	Physical + Stabilization Pond	Natural
Secondary	Anaerobic + Facultative	Natural
Secondary	Trickling Filter (TF)	Package
Secondary	Rotating Biological Contactor (RBC)	Package
Secondary	Conventional Activated Sludge	Package
Secondary	Sequencing Batch Reactor (SBR)	Package
Secondary	Membrane Bioreactor (MBR)	Package
Secondary	Conventional Activated Sludge	CAS
Secondary	Extended Aeration Activated Sludge	EAAS
Secondary	Electroflocculation	Electroflocculation
Advanced	3/4/5 Stage Bardenpho (Partial N&P removal)	Bardenpho
Advanced	Simultaneous Bardenpho	Bardenpho
Advanced	(6/7 Stage) Cascade Activated Sludge	CAS + N, P
Advanced	Conventional Activated Sludge + N, P	CAS + N, P
Advanced	Extended Aeration Activated Sludge + N	EAAS + N, P
Advanced	Extended Aeration Activated Sludge + N, P	EAAS + N, P
Advanced	Sequencing Batch Reactor (SBR) + N, P	SBR + N, P
Advanced	Three Stage Phoredux (Anaerobic/Anoxic/Oxic)	A2O

*For abbreviations see ACRONYMS AND SYMBOLS.

3.2.1.2 Data Regarding Electricity Consumption

HOMER software requires the electrical load data as electricity consumption per day of a month (kWh/d) and assumes daily consumption is constant during the month. As the collected data for electricity consumption of individual WWTPs are annual, the monthly consumption was assumed to be constant and the annual data was distributed evenly to days by assuming that the number of days in a year is 365.

Energy intensity is strongly correlated with the volume of treated wastewater and the type of treatment (see Section 4.1 for details). For the WWTPs of which electricity consumption data is missing (see Table 3.25), a model was developed based on energy intensity analysis of the available data.

Table 3.25. Availability of the electricity consumption and process data

		Electricity Consumption		
		Exist	Not exist	Total
Process Data	Exist	243	**120** *(calculated)*	363
	Not exist	0	93	93
	Total	**243**	213	456

The load is calculated for WWTPs of which electricity consumption data is missing according to the following equation 3.7**Error! Reference source not found.**, where $EC_{unknown}$ (kWh/y) is the annual electricity consumption of the WWTP of which EC is unknown, TWW (m^3/y) is the annual amount of treated wastewater in the WWTP, and the EI (kWh/m^3) is the energy intensity of the specific category of the WWTP of which EC is unknown.

$$EC_{unknown} = TWW \ast \mathrm{EI}_{category} \tag{3.7}$$

3.3 Simulation Program

HOMER basically needs some general information on electrical load (electricity consumption) and the components consist of the system *i.e.* generator, PV, inverter, and grid. The schematic of the installed system is shown in Figure 3.9. The schematic is the same for all the WWTPs. While the location, load, biomass resource, and gasification ratio were entered specifically to each WWTP.

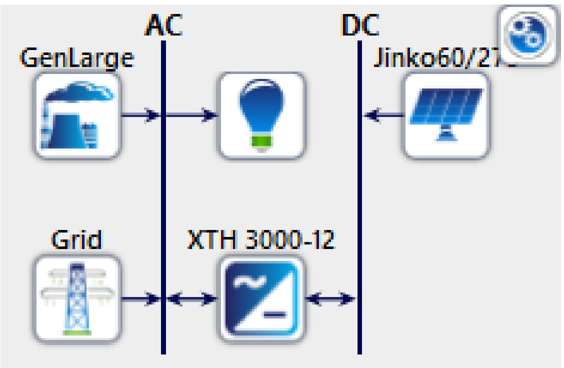


Figure 3.9. System schematic from HOMER Software

To verify the feasibility of the system with the assumptions made, the simulation was run for 13 WWTPs of which data are close to complete. The simulated systems for verification do not have the PV system to represent the current situation.

Following verification, the simulation model was run for each plant of which data was collected because the optimum solution should be different for each plant. The total impact of the integration of RESs to WWTPs in Turkey was presented as aggregated results instead of individual plants.

Location

On the homepage of the software, the location of the WWTP was chosen as a first step (see Figure 3.10).

Figure 3.10. Location finder of the HOMER software

Renewable Energy Resources

Only solar and bioenergy were assessed within the scope of this study as expressed earlier. To include the location of the system will let HOMER download the solar and temperature data on the resources tab from the internet (NREL) according to the given location (see Figure 3.11).

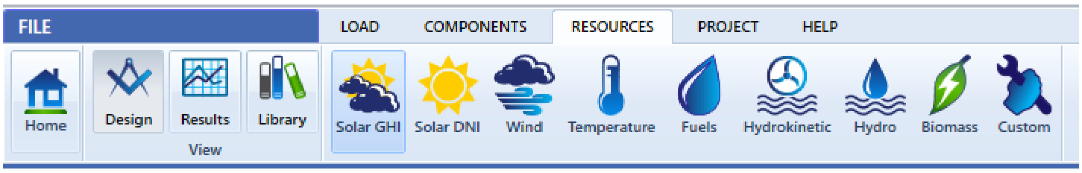


Figure 3.11. Resources tab of the HOMER software

To include bioenergy, the amount of available biomass should be given to HOMER from the Biomass window (see Figure 3.11). Since it was assumed that the monthly biomass production is constant, the annual amount of biomass resource was distributed to months equally. The scaled annual average (t/d) value was changed according to the individual WWTPs. Average price, carbon content, gasification ratio and LHV of the biomass resource was also given to HOMER at this screen.

Components

The components tab is used to insert components such as PV panel, converter, grid and biogas generator (see Figure 3.12). All the parameters of the selected components were given to the software as specified in the previous section on the related page of the software.

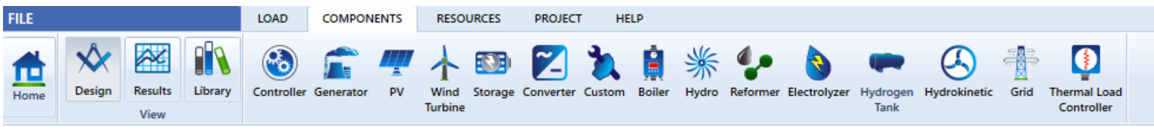


Figure 3.12. Components tab of the HOMER software

The size of the PV panel and the converter were optimized by HOMER according to the system need in each scenario run. The upper limit was chosen as 4,000 kW. As HOMER does not provide an optimizer option for generator size (see Figure 3.13) the options were chosen ranging from 0 to 4,000 kW by an increase of the needed amount of the simulated system. Consequently, HOMER simulates the system with all the capacity options and accordingly decides the optimum option (the option with the lowest Net Present Cost-NPC).

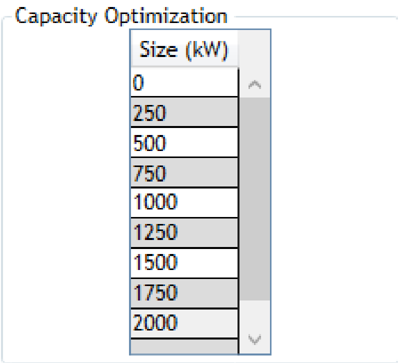


Figure 3.13. Generator capacity options input field example in the HOMER software

Electricity Consumption

On the LOAD tab, available and calculated electricity consumption of each WWTP was given to the system with the scaled annual average (kWh/day) box on the bottom of the screen (see Figure 3.14). To obtain daily consumption, annual consumption values were divided by 365. The given value was distributed hourly based on the selected consumer profile. The daily profile of the load, in other words, hourly distribution of the electricity consumption, was assumed to be constant as the WWTPs of the municipalities generally works 7/24 hours.

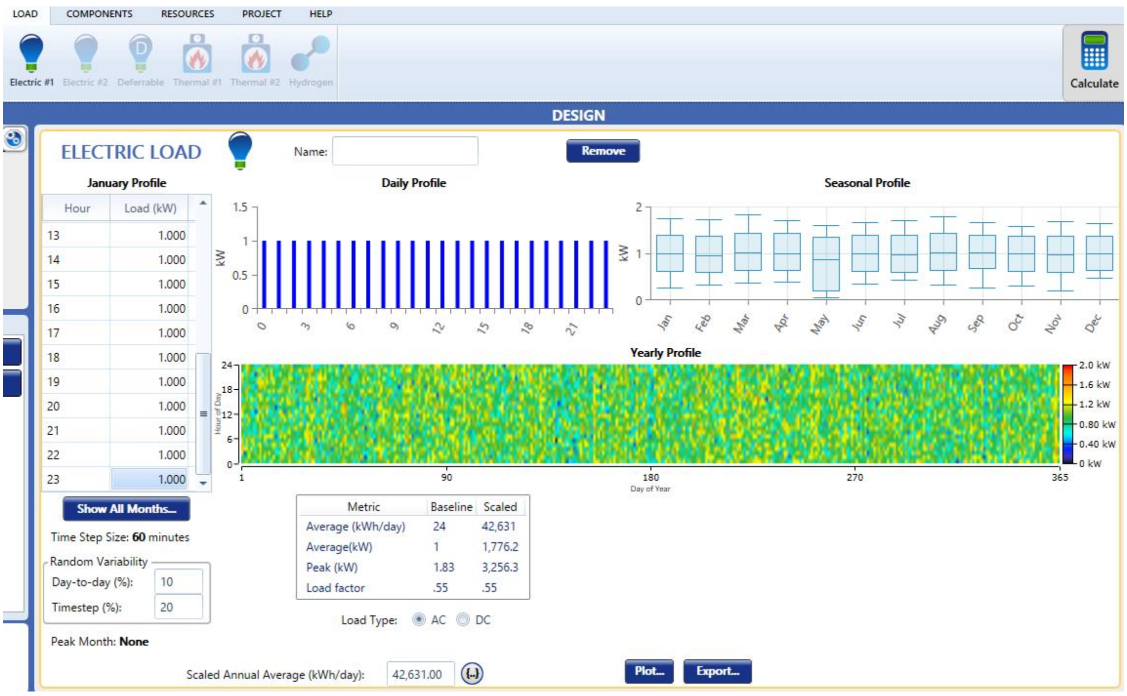


Figure 3.14. Load introduction screen of the HOMER software

Overall System

On the projects tab (see Figure 3.15), the project-related data *i.e.* economic parameters and emission penalties were given to the system based on assumptions in the previous section.

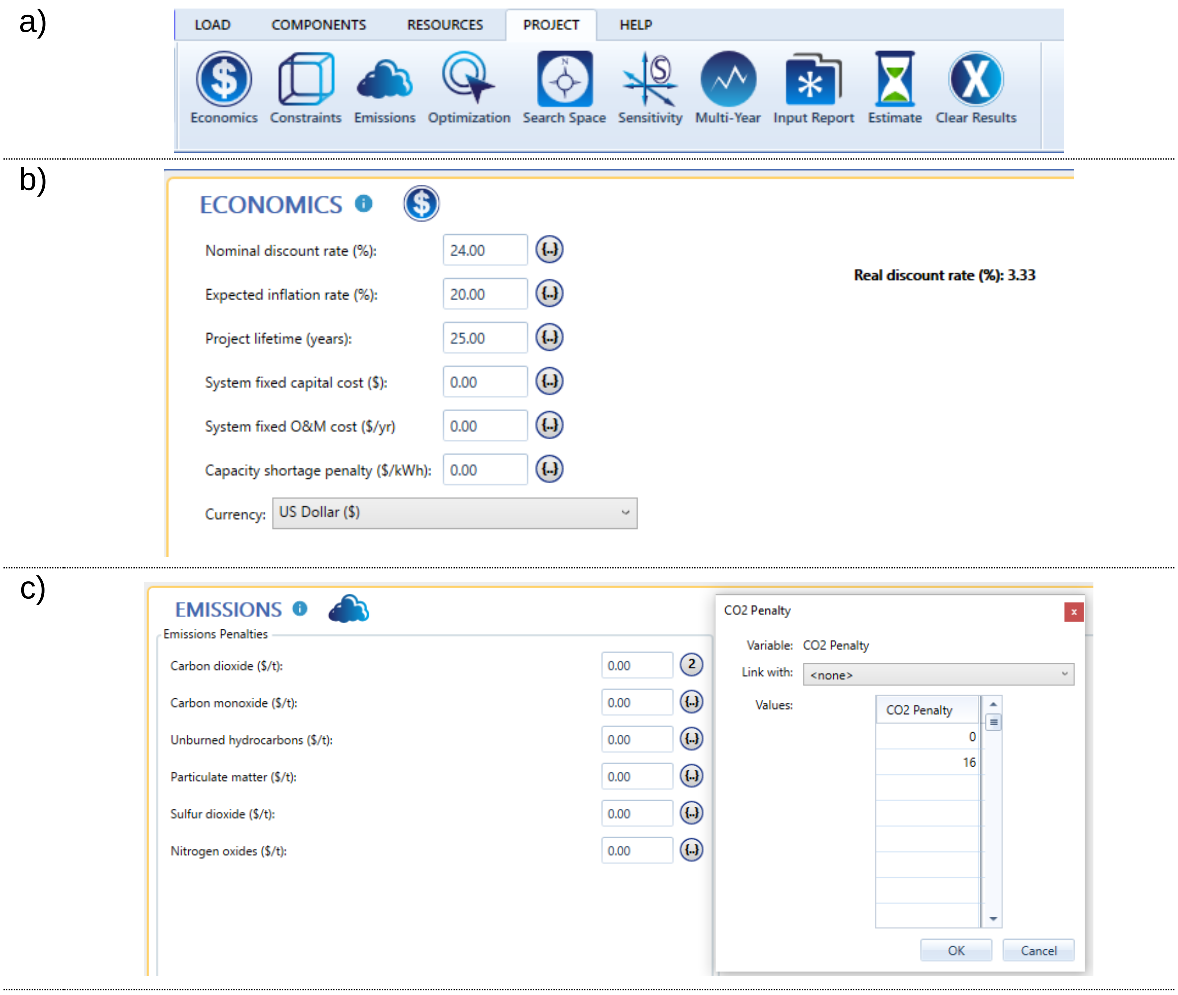


Figure 3.15. a) Project tab, b) Economics tab, and c) Emissions tab of the HOMER

3.4 Limitations

The number of participants in the survey conducted within the scope of this study does not create a large representative sample. The survey results can not indicate a valid result for the whole WWTPs. Yet, a tendency, that is in parallel with the findings in the literature, can be seen in this small sample of responses as it is shown in the Results chapter.

The WWTPs considered within this study are limited to the ones given in AARs. In case of filling the data gap, personnel of some of the WSAs provided data for additional WWTPs. However, the total number of WWTPs used in this study still less than the total number of WWTPs in the metropolitan municipalities.

The parameters of WWTPs are limited with the given information in the open literature and personal communication. For instance, some WWTPs applied minor modifications to the original process used in the plant, resulting in a change in the type of the WWTP. Therefore, a process defined as a secondary treatment in the reports, for example, might be an advanced treatment for a WWTP which modified the process slightly. This kind of information is not available for this study unless it was indicated by the WWTPs itself during personal communication. Another similar example could be given for treated wastewater or the electricity consumption, which could be different values in different open sources. In this case, the value given in the AAR was used unless a different value was reported by the WWTPs during personal communication.

In addition, only the WWTPs of which data are missing were contacted. The information regarding the rest of the WWTPs found in the open literature were assumed to be right.

The simulation results of this study are limited by the assumptions made throughout the study. In the real world, the characteristics of WWTP will impact most of the assumptions made regarding biogas power. The fluctuations in the economic parameters is another impact on the results. Thus, it is important to evaluate the simulation results of this study as a basis for further detailed analysis.

3.5 Concluding Remarks

In this chapter, the data sources and the methodology are detailly explained. As almost in every study, this thesis depends basically on data collection for the main parameters needed in the simulation model. Following the collecting of data by using various tools such as online survey, telephone, fax, mail, literature research, market research, *etc.*, the collected data analyzed in order to develop assumptions and calculation methods for each parameter. The parameters were used in the HOMER software to simulate the possible and optimum RESs combinations to meet the electricity demand of the WWTPs. Finally, the individual economic and environmental simulation results are combined to obtain an overall result for Turkey.

The parameters used in the software are given in Table 3.26 while the partial tables are given in the related sections of this chapter.

Table 3.26. Summary table for the used values in the simulation model

	Data	Unit	Range	Source	Used Value
Biomass Resource	Available Amount (Sludge production in individual WWTPs)	ton/day	N/A	Field Data	PS[a]
	Average Price	\$/ton	22.1	[49]	22.1
	Carbon Content	% of mass	19 - 50	[53]–[58]	35
	Gasification Ratio (biogas to biomass)	kg/kg	N/A	Field Data	PS[a]
Biogas Fuel	Density	kg/m^3	1.10 - 1.25	[46], [66]–[69]	1.2[b]
	Lower Heating Value (LHV)	MJ/kg	13.3 – 23.2	[48], [60], [66]–[68]	19[b]
Generator	Initial Capital of generator	\$/kW	420 – 7,220	[42], [46], [51], [71]–[77]	2,000
	Replacement Cost of generator	\$/kW	N/A	Assumption	2,000
	Cost of O&M of generator	\$/kW-op.h.	0.012-0.021	[42], [51], [73]	0.015
	Lifetime	k hours	48 – 60	[42], [77]	60
	Fuel Consumption	kg/kWh	N/A	HS[c]	0.014[d] 0.244[e]
	CO	g/kg fuel	4.9 – 15.8	[78]–[81]	8
	Unburned HC	g/kg fuel	2.5 – 4.8	[78], [81]	3.2
	Particulate Matter	g/kg fuel	0.00029	[78]	0.00029
	Fuel Sulfur to PM	%	N/A	Assumption	0
	NO_x	g/kg fuel	3.6 – 10.3	[78]–[81]	5.5
Solar Resource	Local solar radiation (GHI)	kWh/m^2-day	N/A	HS[a]	PS[b]
	Clearness Index	%	N/A	HS[a]	PS[b]
	Temperature	^{o}C	N/A	HS[a]	PS[b]
	Location (District of the WWTP)	N/A	N/A	Field Data	PS[b]
Photovoltaic Panels	Investment Cost of PV system	\$/kW	900 - 1,500	[38], [42], [88]–[90], [70], [71], [82]–[87]	1,100
	Replacement Cost of PV system	\$/kW	0	[85], [89]	0

	Data	Unit	Range	Source	Used Value
	Cost of O&M of PV system	$/y-kW	10.0 - 19	[70], [87], [89], [91]–[93]	12
	Lifetime	years	25	MR[c], HS[a]	25
	Derating Factor	%	N/A	HS[a]	88
	Ground Reflectance (albedo)	%	N/A	HS[a]	20
	Temperature Coefficient of Power	%/ ^{o}C	-0.37- - 0.47	MR[c], HS[a]	-0.41
	NOCT	^{o}C	43 - 47	MR[c], HS[a]	45
	Efficiency at STC	%	15.7 - 19.6	MR[c], HS[a]	16.8
	Azimuth Angle	^{o}	0 - 180	HS[a]	0
	Slope Angle	^{o}	~	HS[a]	PS[b]
Inverter	Investment Cost of Inverter	$/kW	37.3 – 1,000.0	[42], [70], [72], [83], [85], [88], [89], [91], [94]	110
	Replacement Cost of Inverter	$/y	N/A	Assumption	110
	Cost of O&M of Inverter	$/y-kW	N/A	Assumption	0
	Input Lifetime	years	N/A	HS[a]	10
	Input Efficiency	%	N/A	HS[a]	93
	Rectifier Relative Capacity	%	N/A	HS[a]	100
	Rectifier Efficiency	%	N/A	HS[a]	93
Grid	Grid Power Price	$/kWh	0.0647 - 0.0849	[95], Field Data	0.080
	Grid Sellback Price	$/kWh	N/A	[96]	0.133 & 0.050 & 0
	CO_2	g/kWh	482.80 - 499.87	[98], HS[a]	482.80
	CO	g/kWh	0.00 - 0.24	[97], HS[a]	0.24
	Unburned HC	g/kWh	0.00	HS[a]	0.00
	Particulate Matter	g/kWh	0.00 - 0.22	[97], HS[a]	0.22
	SO_2	g/kWh	1.82 - 2.74	[97], HS[a]	1.82
	NO_x	g/kWh	0.57 - 1.34	[97], HS[a]	0.57
Economics	Nominal discount rate	%	N/A	[101]	24
	Expected inflation rate	%	19.7 - 20.3	[102], [103]	20
	Project Lifetime	years	N/A	HS[a]	25
	System fixed capital cost	$	N/A	Assumption	0
	System fixed O&M cost	$/y	N/A	Assumption	0
	Capacity Shortage Penalty	$/kWh	N/A	HS[a]	0
Emission Penalties	CO_2	$/ton	0.08 – 126.78	[104]	16 & 0
	CO	$/ton	N/A	Assumption	0
	Unburned HC	$/ton	N/A	Assumption	0

	Data	Unit	Range	Source	Used Value
	Particulate Matter	$/ton	N/A	Assumption	0
	SO_2	$/ton	N/A	Assumption	0
	NO_x	$/ton	N/A	Assumption	0

[a] Plant Specific
[b] These values were used in the conversion of some parameters given with various units in the literature.
[c] Homer Software
[d] Intercept coefficient of the fuel-power curve
[e] Slope of the fuel-power curve

4 RESULTS AND DISCUSSION

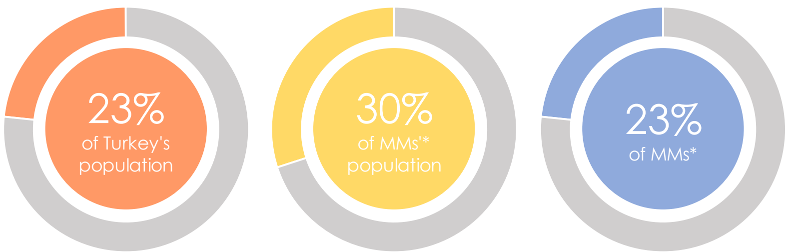
In this chapter the results of the study are presented in the following four contents;

- ✓ Survey results,
- ✓ Analysis of the collected data,
- ✓ Energy intensity of WWTPs in Turkey,
- ✓ Simulation outcomes.

4.1 Survey Results

As indicated in the previous chapter, the survey has two main parts. One part is to reveal the energy consumption of WWTPs. The second one is to get the participants' evaluation of RES integration to WWTPs.

Answers of 20 WWTPs operators were valid to be evaluated as indicated before. These WWTPs are in 7 metropolitan municipalities, representing 23% in terms of number, and 30% in terms of population of metropolitan municipalities in Turkey. They also represent 23% of the population of Turkey (see Figure 4.1). 70% of them employ advanced treatment while the rest of them use secondary treatment.

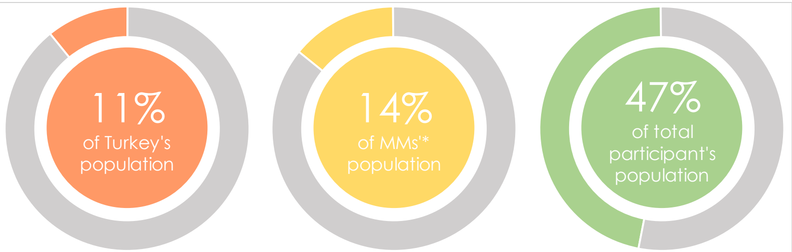


*MM: Metropolitan Municipalities

Figure 4.1. Representativeness of survey participants

4.1.1 Energy Resources and Consumption of WWTPs

The total number of WWTP operators participated in the first part of the survey is 20, so the representation ratio is 100% for the survey participants. The total population that is served by these WWTPs consists of 47% of participant cities in terms of population. They also comprise 11% and 14% of the population of Turkey and metropolitan municipalities, respectively (see Figure 4.2).

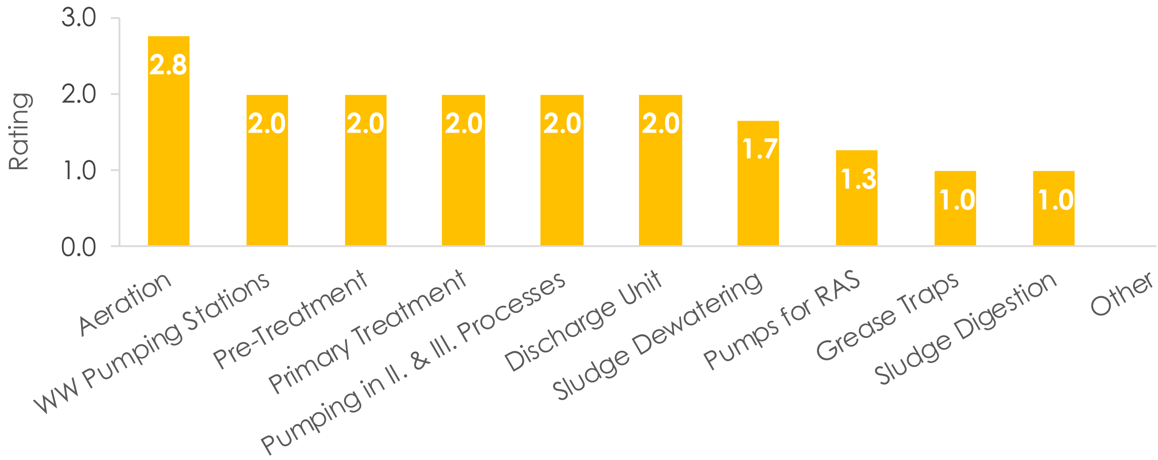


*MM: Metropolitan Municipalities

Figure 4.2. Participants' representativeness for the first part of the survey

In the first part of the survey, WWTP operators were asked questions related to the plants' electricity consumption. One of the questions required the participants to select the top three in electricity consuming processes (see Appendix A). A list of 25 processes and sub-processes were given to the participants and they labeled them as the 1st, 2nd, and 3rd electricity consumer in the plant. Participants could either select directly the main process such as primary, secondary & advanced, sludge processes, *etc.* or the subprocesses such as sludge digestion, aeration, *etc.*

For the assessment of the responses, the sub/process selected as the 1st was given a rating of three and vice versa. Therefore, their ratings were evaluated based on a full point of three. 10 processes in 25 were labeled as being in the top three consumers at least once. Aeration was chosen as the top one consumer (see Figure 4.3). As was expected, the results validate that the electricity consumption of aeration is much higher than other sub/processes.



RAS: Return Activated Sludge

Figure 4.3. Processes selected as top three electricity consumers in WWTPs

In another question of the first part of the survey asked participants to give the electricity consumption of each individual process as a percentage of the total electricity consumption of WWTP. The participants were given the same sub/processes list with the previous question. The sub/processes which have the greatest number of data were taken in the evaluation and consequently, 6 processes were evaluated. During the assessment, it was realized that the main process called “pre-treatment” and its subprocess called “WW pumping stations” were perceived as separate processes as the percentage of the subprocess was given as higher than its main process. Therefore, they were treated as separate processes in the evaluation.

Based on the assessment, the distribution of the median values of inputs for each sub/process revealed that the aeration has the biggest electricity consumption with a share of 40% (see Figure 4.4). This conclusion supports the output of the previous question as aeration was evaluated as the biggest electricity consumer with a ranking of 2.8 over 3 (see Figure 4.3). In the literature, aeration is also the biggest electricity consumer with a share of generally between 50-60%, and there are cases where its share is as low as 13% and reaches up to 70% as it depends on the size of the WWTP and content of the wastewater [16], [19], [21], [23], [25], [105], [106].

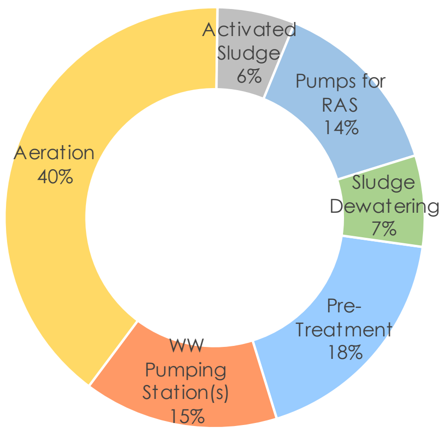


Figure 4.4. Median electricity consumption shares of sub/processes

Aeration is followed by pre-treatment, WW pumping stations and pumps for return activated sludge (RAS) (see Figure 4.4). According to various researches on electricity consumption of the WWTPs, WW pumping generally comes after aeration in electricity consumption with a share of changing from 4 to 30% with a typical value of 15-20% while it can reach up to 60% in some cases [16], [19], [21], [23], [26], [106]. The variation of the share of WW pumping is also validated by the literature as seen in Figure 4.5. The maximum variation is seen on activated sludge. That might be attributable to the participants' different definitions for the scope of the activated sludge process.

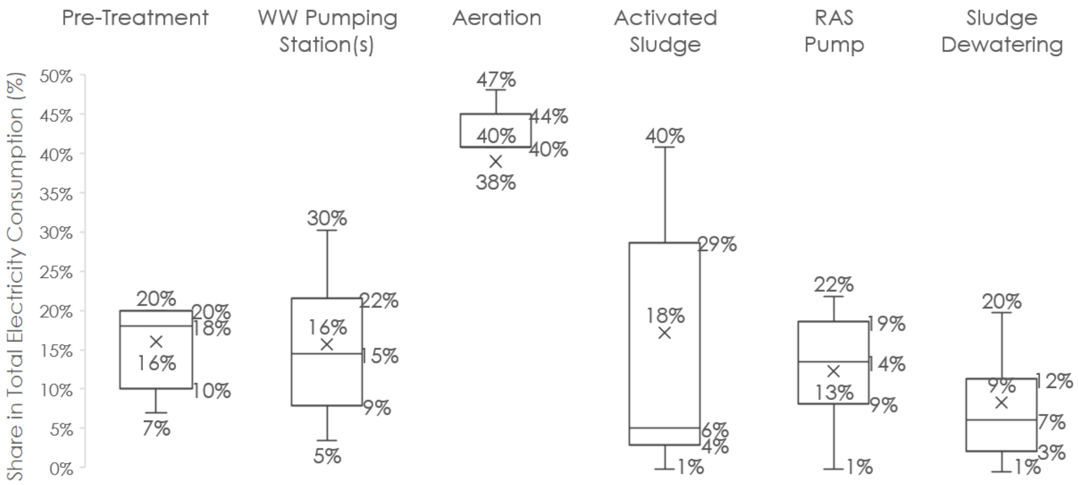


Figure 4.5. Given electricity consumption shares of sub/processes in total consumption

4.1.2 Perception of Renewable Energy Integration to WWTPs

The second part of the survey has questions on the opinions of WWTP operators about RES integration to WWTPs to comprehend the perception on the topic. Responses were collected for 20 WWTPs with 100% representation of the participants. Yet, the number of responses that were evaluated is less for this section of the survey. Because the same responses came from the same personnel who participated in the survey for different WWTPs under a municipality were omitted. Therefore, 13 responses were taken into account for the assessment. They comprise 43% of the total population of participants, 10% of Turkey's and 13% of metropolitan municipalities (see Figure 4.6).

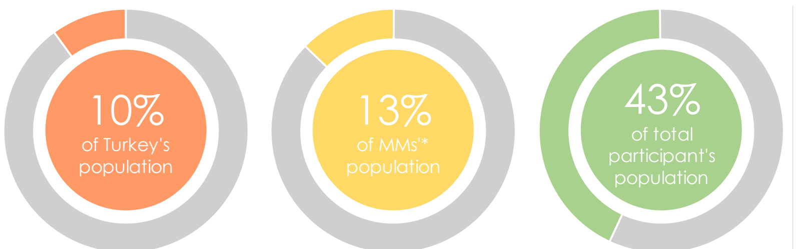


Figure 4.6. Participants' representativeness for the second part of the survey

The first question of the perception section is about Renewable Energy Resources Support Mechanism (YEKDEM) in Turkey. The participants were asked whether the mechanism is supportive of the WWTPs to implement RES. They were supposed to rate from 1 (not supportive at all) to 5 (very supportive). Their responses mainly focused on the rate of three (see Figure 4.7) which means YEKDEM has no positive or negative impact for WWTPs on deploying RES.

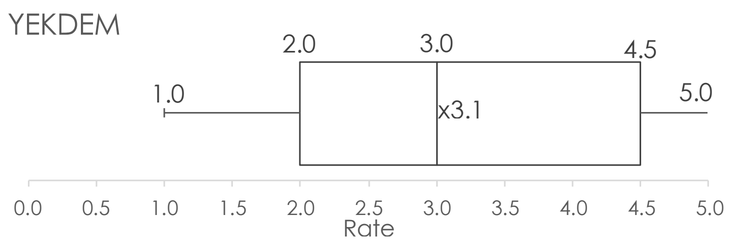


Figure 4.7. Rate of supportiveness of YEKDEM for WWTPs to integrating RES

The second question was about the barriers for WWTPs towards integrating RES. The participants were given five pre-defined barriers. They could choose more than one option and add additional options. According to their responses, the main barrier was found to be economical (see Figure 4.8) followed by technological barriers.

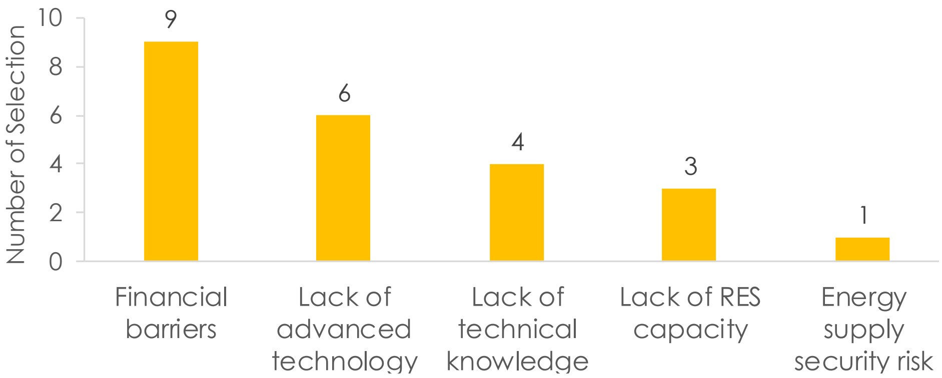


Figure 4.8. Barriers for WWTPs to integrating RES

The third question was on several motivating factors for WWTPs to integrate RES. The participants were given 11 pre-defined factors and they were asked to rate each between 1 (not motivating at all) to 5 (very motivating). According to their responses, almost all the factors except “improving voltage and frequency management”, have a motivating impact with a rating of higher than three (see Figure 4.9).

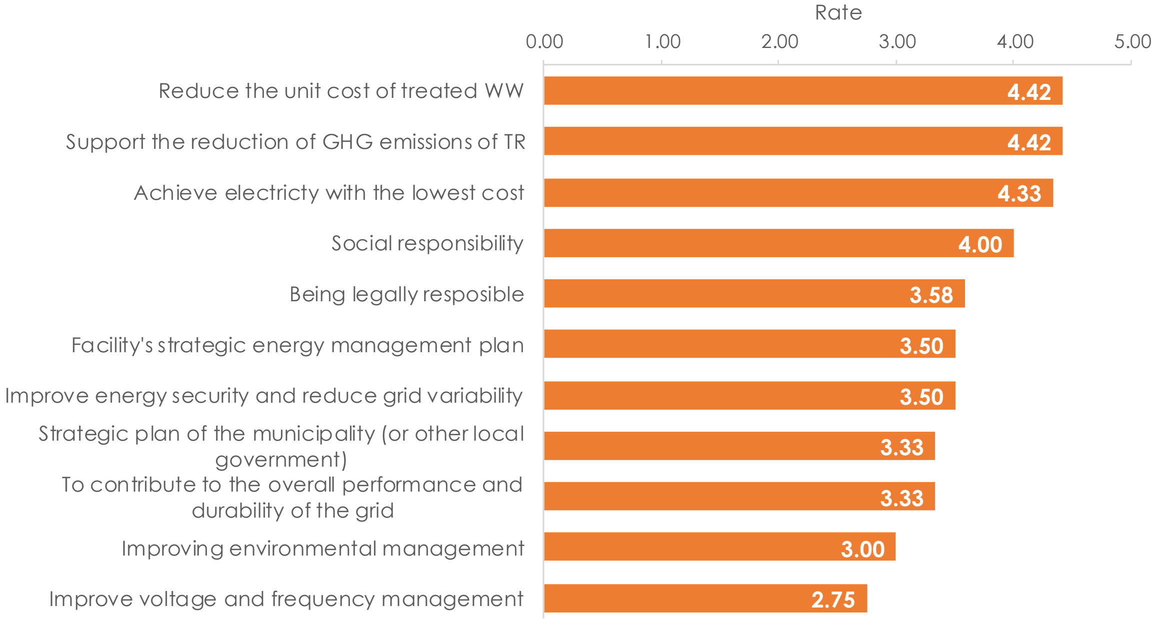


Figure 4.9. Motivating factors for WWTPs to integrating RES

In the fourth question, the participants were asked about renewable energy technologies which are common today and will take place in 10 years. In both categories, PV has the first line (see Figure 4.10).

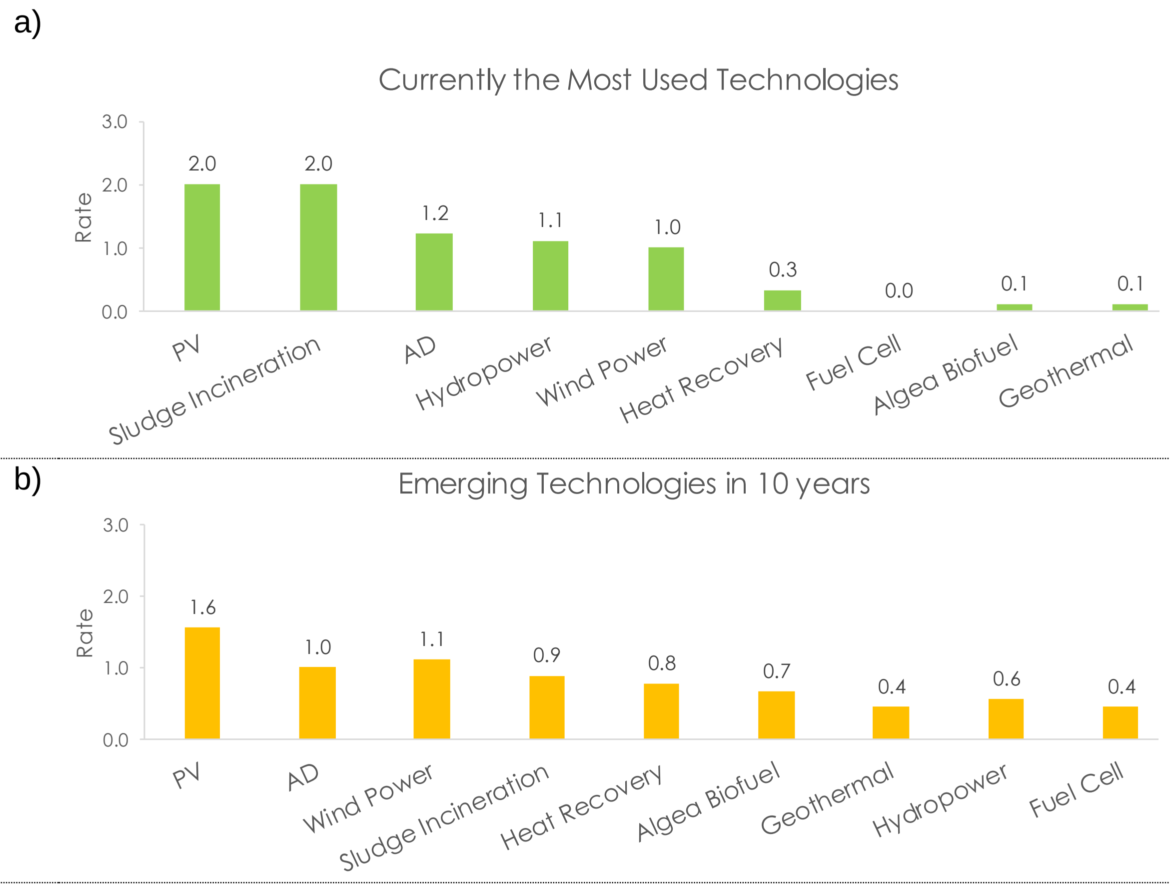


Figure 4.10. RES technologies a) Currently the most used b) Emerging in 10 years

The fifth question was about electricity storage. The participants were asked whether they use electricity storage and whether they have a plan to increase its capacity. Two of the five participants having electricity storage are planning to increase electricity storage capacity (see Figure 4.11). On the other hand, one of the 7 participants not having electricity storage is planning to have.

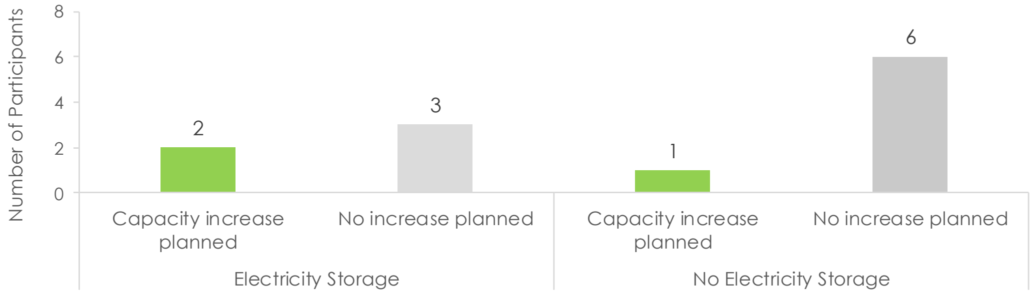


Figure 4.11. Electricity storage existence and capacity increase planning

For the final, sixth, question the participants were asked whether they implement any measures to reduce the electricity consumption of the WWTPs. 64% of them indicated that they implemented reduction measures (see Figure 4.12). Soft starter and frequency converter utilization in electromechanics, and process control are some of these measures indicated by the WWTP operators.

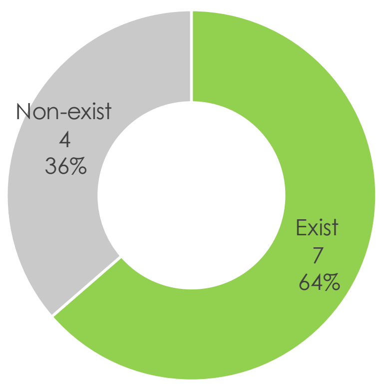


Figure 4.12. Existence of electricity consumption reduction measures

4.2 General Analysis of the Collected Data

The data on various parameters of WWTPs of 30 metropolitan municipalities in Turkey was collected (see Section 3.1). In total, 818 data inputs for 481 WWTPs were obtained for different years. Since the scope of the thesis is the year of 2017, mainly the data for 2017 was intended to be completed. As a result, the data of 456 of 481 WWPTs was gathered and completed for 2017 (see Figure 4.13). The following analysis is based on these 456 WWTPs. According to the MoEU WWTPs inventory in May 2018, there are 911 WWTPs in Turkey. 456 WWTPs, of which data were collected, represent 50% of the WWTPs in number. The cities, in which these WWTPs are located, represent 77% of Turkey's population in 2017 [107].

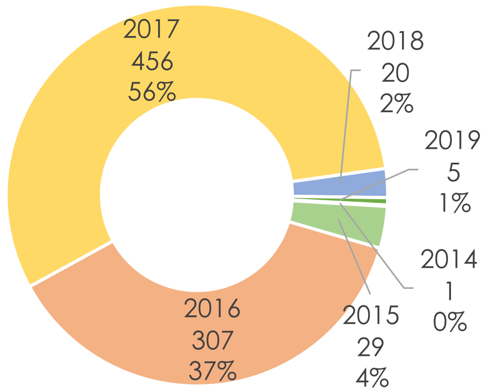


Figure 4.13. Number of total collected WWTPs data for 2014-2019

The existing detailed data in each topic is shown in Figure 4.14. Type information of 456 WWTPs is available, while processes used the plant were identified for 80% of them. The percentage of the known data in electricity consumption and the discharged sludge is relatively low; i.e. 53% and 46% respectively.

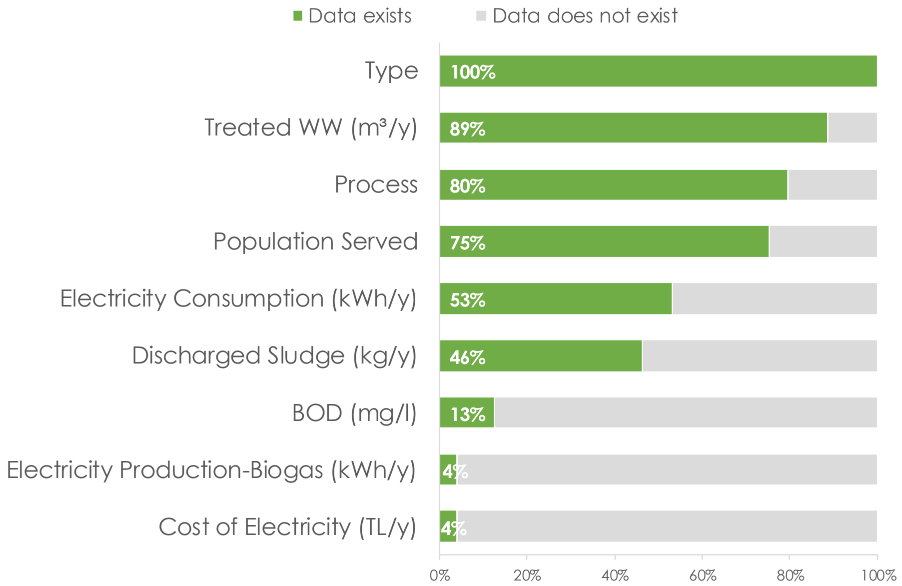


Figure 4.14. Share of available data among the collected ones for 2017

66% of the WWTPs of which data was collected is secondary treatment, while 22% is advanced treatment. The rest is distributed as natural, primary and package WWTPs (see Figure 4.15).

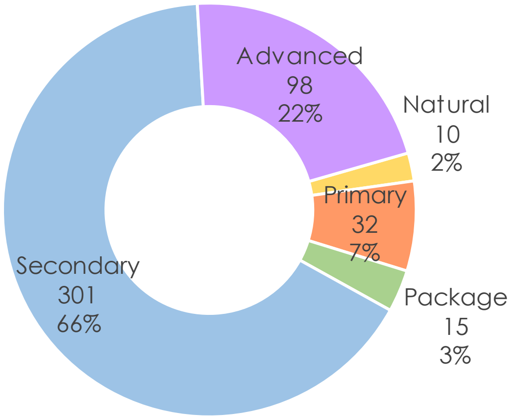


Figure 4.15. Collected WWTPs by treatment type

The process category distribution (see Section 3.2 for details) of the 456 WWTPs is shown in Figure 4.16. As can be clearly seen, 18% of the WWTPs use EAAS while 29% use CAS. On the other hand, 20% of the collected WWPTs' processes are not known as shown in Figure 4.14 before.

42% of the WWTPs treat up to 500,000 m^3 of wastewater while 35% treat between 500,000 and 10 million m^3 (see Figure 4.16).

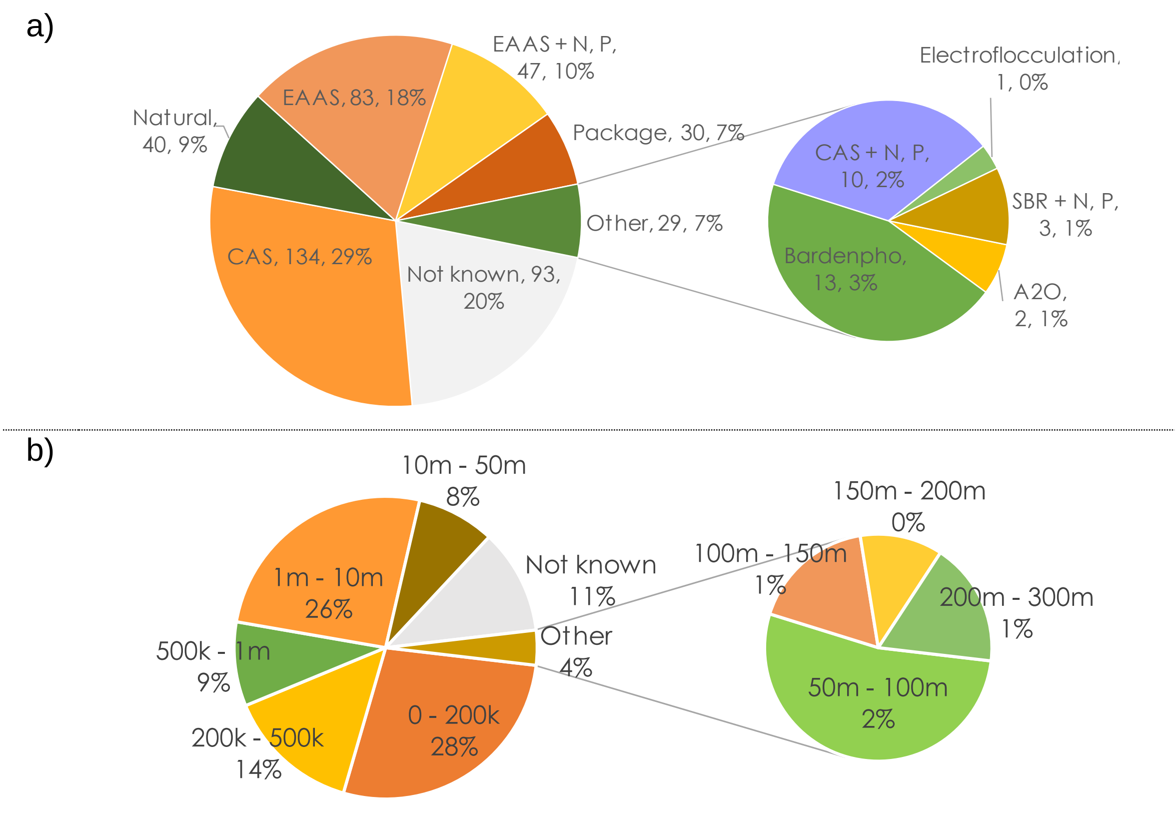


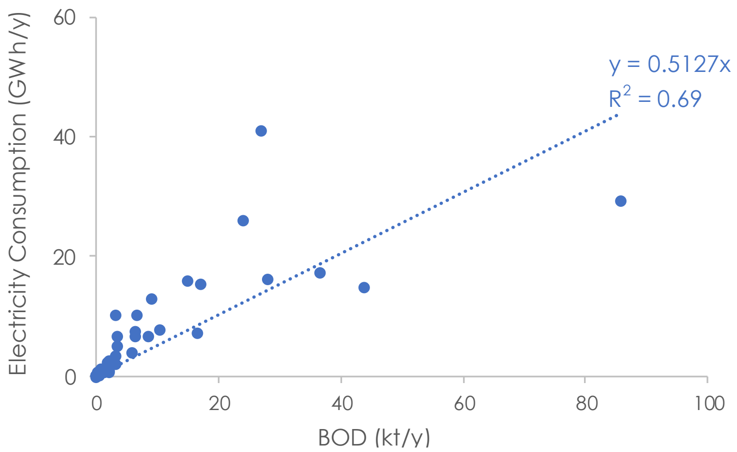
Figure 4.16. Collected WWTPs a) by process b) by volume of treated wastewater

4.3 Energy Intensity Calculation Results

Before calculation of the energy intensity, the relationships between total energy consumption (EC) (kWh/y) and aforementioned parameters that have an impact on the electricity consumption of WWTPs *i.e.* BOD (kg/y) and the amount of treated wastewater (TWW) (m^3/y) were inspected. Simple regression analysis (RA) with a confidence interval of 95% was employed for the investigation and the constant was assumed to be 0.

In Figure 4.17 the correlation of EC (kWh/y) with the BOD (kg/y) and the TWW (m^3/y) are presented based on available data. Electricity consumption (kWh/y) of the WWTPs is 69% correlated with BOD, while 68% correlated with the TWW (see Figure 4.17). In some studies, even higher correlation values such as 80-95% were observed [24], [25], [106]. Molinos-Senante *et al.* [27] also showed the relation by finding out the share of flow rate among factors that impact EC is at least 30%.

a)



b)

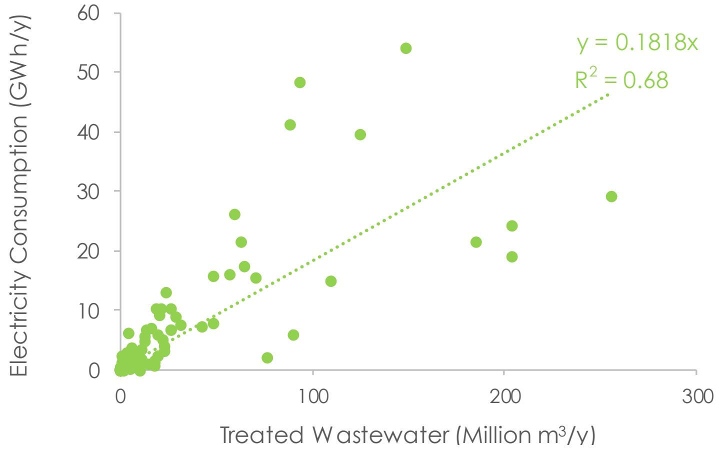


Figure 4.17. a) Correlation between total electricity consumption and BOD b) Correlation between total electricity consumption and flow rate

According to analysis results, p-values are too low indicating that the correlation is significant and the relation equations can be used for estimation of the total electricity consumption (see Table 4.1).

Table 4.1. R^2, F value, and p-value of the regression analysis between electricity consumption (kWh/y) and BOD (kg/y) and treated wastewater (m^3/y)

Total electricity consumption (kWh/y)	R^2	F	p-value (Significance F)
BOD (kg/y)	0.69275252	117.245	7.98894E-15
Flow rate (m^3/y)	0.67728820	501.599	1.58039E-60

The positive relation between the total electricity consumption and flow rate and BOD can be clearly seen in Figure 4.18.

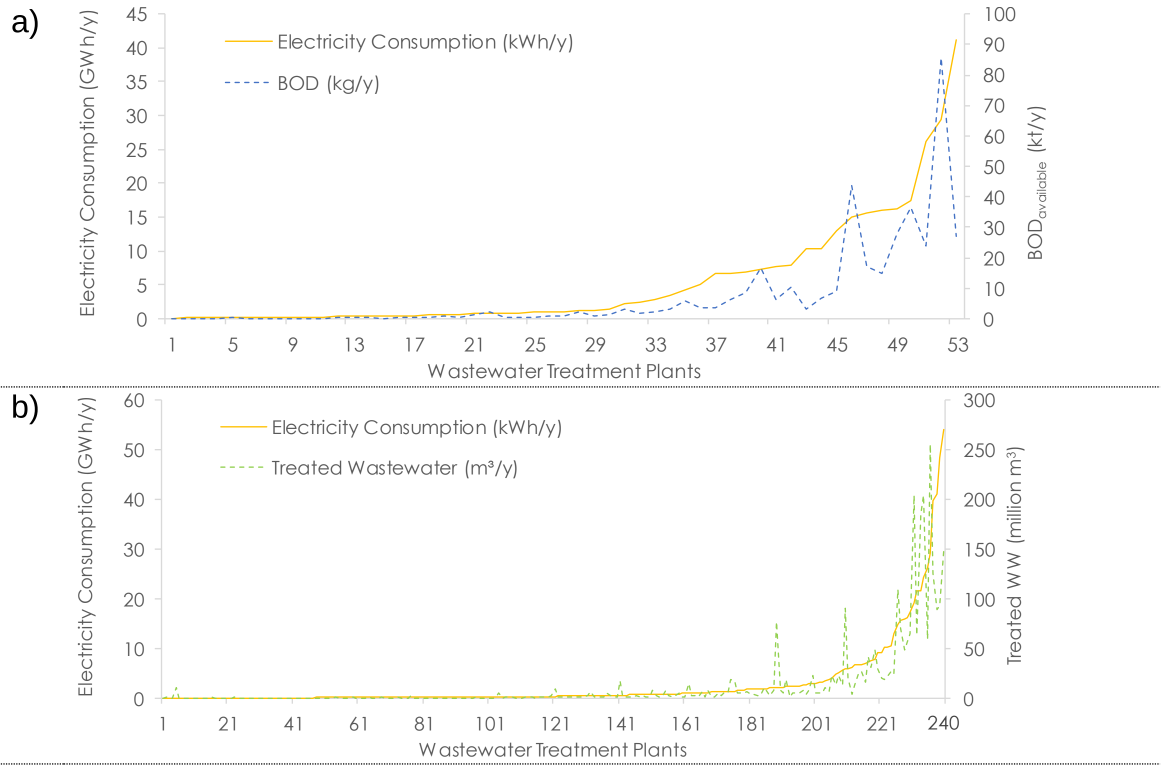


Figure 4.18. Electricity consumption (GWh/y) and a) BOD (kt/y) b) the amount of treated wastewater (million m^3/y)

Electricity consumption per meter cube of treated wastewater, *i.e.* energy intensity (EI) (kWh/m^3), of each WWTPs of which data were available were calculated by using equation 3.6 given in Section 3.2. The outliers in the energy intensity data set including 240 WWTPs, were identified by using Modified Z Score (Median Absolute Deviation-MAD) [108] with double MAD as the skewness of the data set is 5.59

indicating a positive skewness (see Figure 4.19). As chosen the cut-off point of 1.5, in total 25 WWTPs with an EI of below 0.06 kWh/m^3 and above 1.45 kWh/m^3 were identified as outliers (red colored in Figure 4.19), representing 10% of 240 WWTPs. Thus, 90% of the available data was analyzed further.

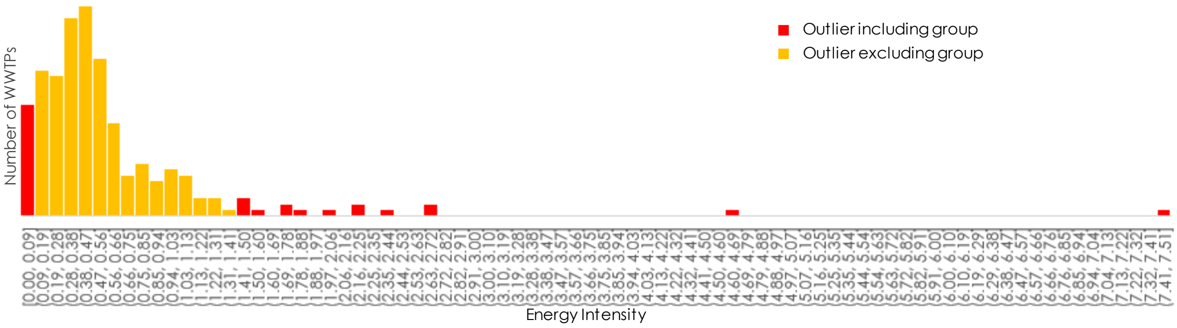


Figure 4.19. Histogram of calculated energy intensities (kWh/m^3) of 240 WWTPs

When the overall energy intensity of Turkey is compared with other countries, Turkey has relatively low energy intensity (see Figure 4.20). The references [19], [24] that were used for the national energy intensity comparison give different values for the same countries *i.e.* China, Germany Japan, Sweden, USA. The difference is huge for the USA and especially for Germany while it is smaller for China and Sweden. Still, the comparison gives an idea of the position of Turkey in the energy consumption of WWTPs among other countries.

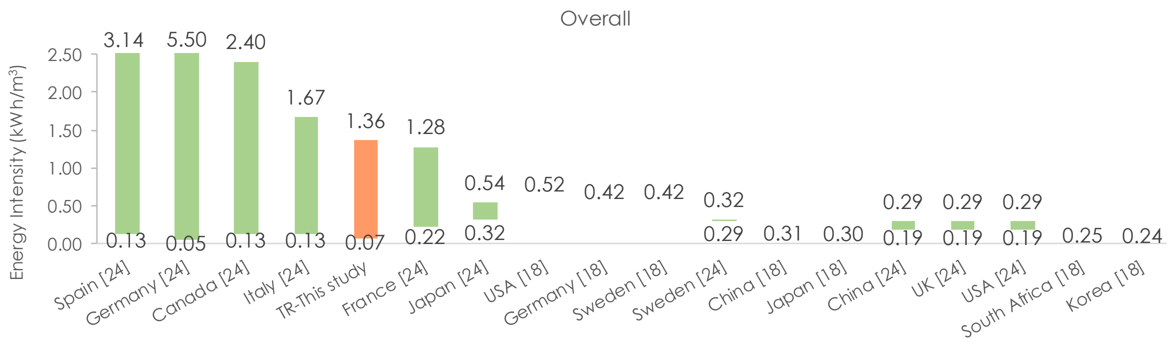


Figure 4.20. National energy intensity comparison with countries (adapted from [19], [24])

Based on the type classification defined in Section 3.2, energy intensities (kWh/m^3) of each type of WWTPs are shown in Figure 4.21. EI is the highest for secondary WWTPs while primary WWTPs have the lowest ones similarly with the findings in the literature research [9], [21]. The distribution looks even and more concentrated although the range is between 0.147 and 0.779 kWh/m^3 for advanced treatments without outlier points. For secondary treatment, on the other hand, the variation is high, and the distribution is wide changing between 0.075 to 1.276 kWh/m^3 (without outliers). Nevertheless, most of the data concentrates on lower values giving a median of 0.45 kWh/m^3.

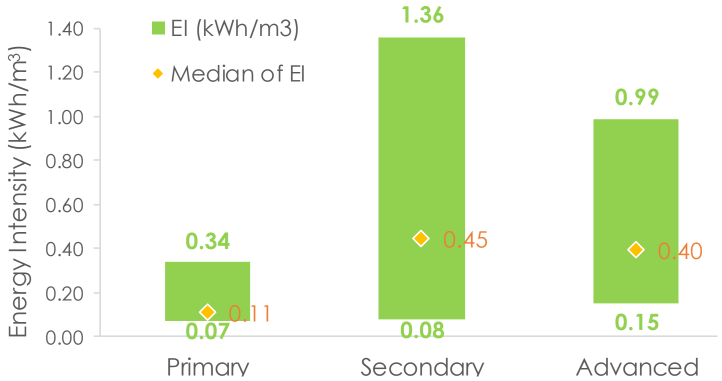


Figure 4.21. Maximum, minimum and median of calculated energy intensity (kWh/m^3) by type in Turkey

When the energy intensity of advanced treatment in Turkey was compared with the values found in the literature [9], [23], [26], Turkey has one of the lowest energy intensity at minimum, however, it has high variation for advanced treatment (see Figure 4.22).

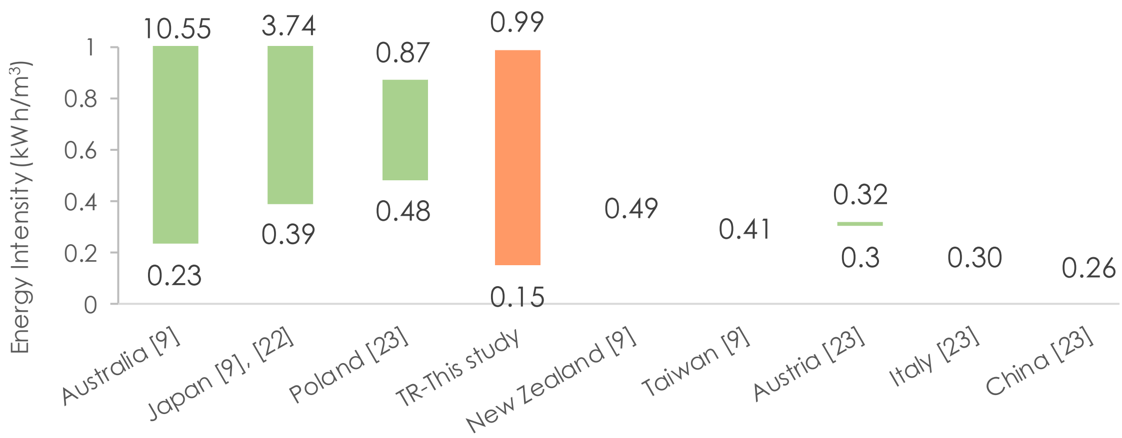


Figure 4.22. Comparison of Turkey's calculated energy intensity for advanced treatment (adapted from [9], [23], [26])

Nonetheless, its variation is not as much as Australia and Japan. For the primary treatment, at the same time, its EI is one of the higher values with a lower deviation compared to Australia and New Zealand (see Figure 4.23).

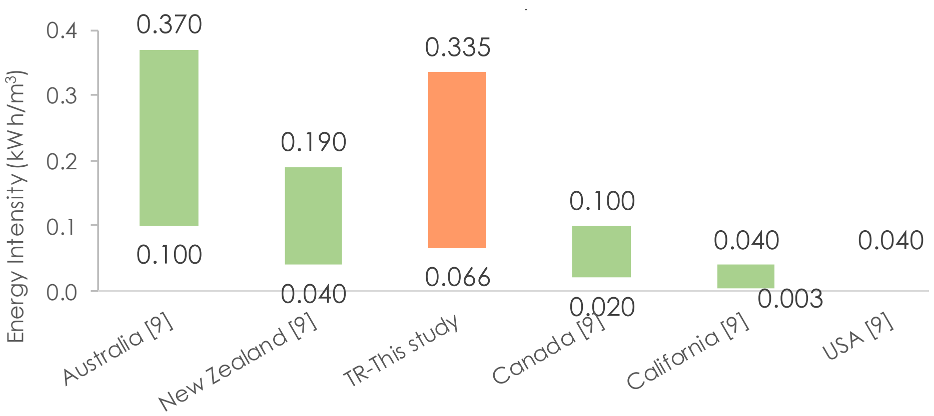


Figure 4.23. Comparison of Turkey's calculated energy intensity for primary treatment (adapted from [9])

As the energy intensity for primary and advanced treatments could be found in the literature as one value, the comparison could be done on type basis. However, finding an overall value for all secondary treatments is harder. Because it has varying techniques changing the energy consumption of the plant significantly. For this reason, energy intensity for secondary treatments compared on process based.

For this purpose, the energy intensities (kWh/m^3) were investigated by their process. The highest energy intensity belongs to CAS, even though median and average values are close to EAAS (see Figure 4.24). This outcome is not in line with the findings from the literature as EAAS in literature has higher EI than CAS's [9], [21], [22], [24] because of the long aeration need and the aeration's contribution to total electricity consumption in the plant as indicated before.

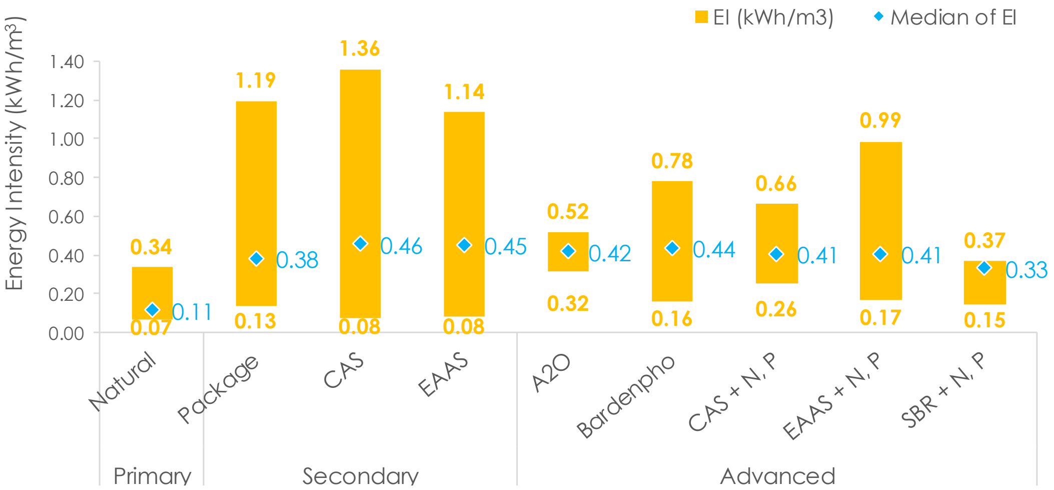


Figure 4.24. Calculated energy intensity (kWh/m^3) by process

The energy intensities of CAS, MBR, and OD in Turkey were compared with other countries (see Figure 4.25). Based on the comparison, OD has closer values to Australia. CAS treatments in Turkey can be categorized as high energy consumers among other countries however they might have also lower energy intensities because of the deviation range it has. The range also includes the result for WWTPs using CAS in the thesis of Ayrak [22] (see Figure 4.25). His energy intensity results for EAAS is also within the range of this study's outcome (0.45 kWh/m^3) with a value of 0.89 kWh/m^3 and higher than the medium value found in this study.

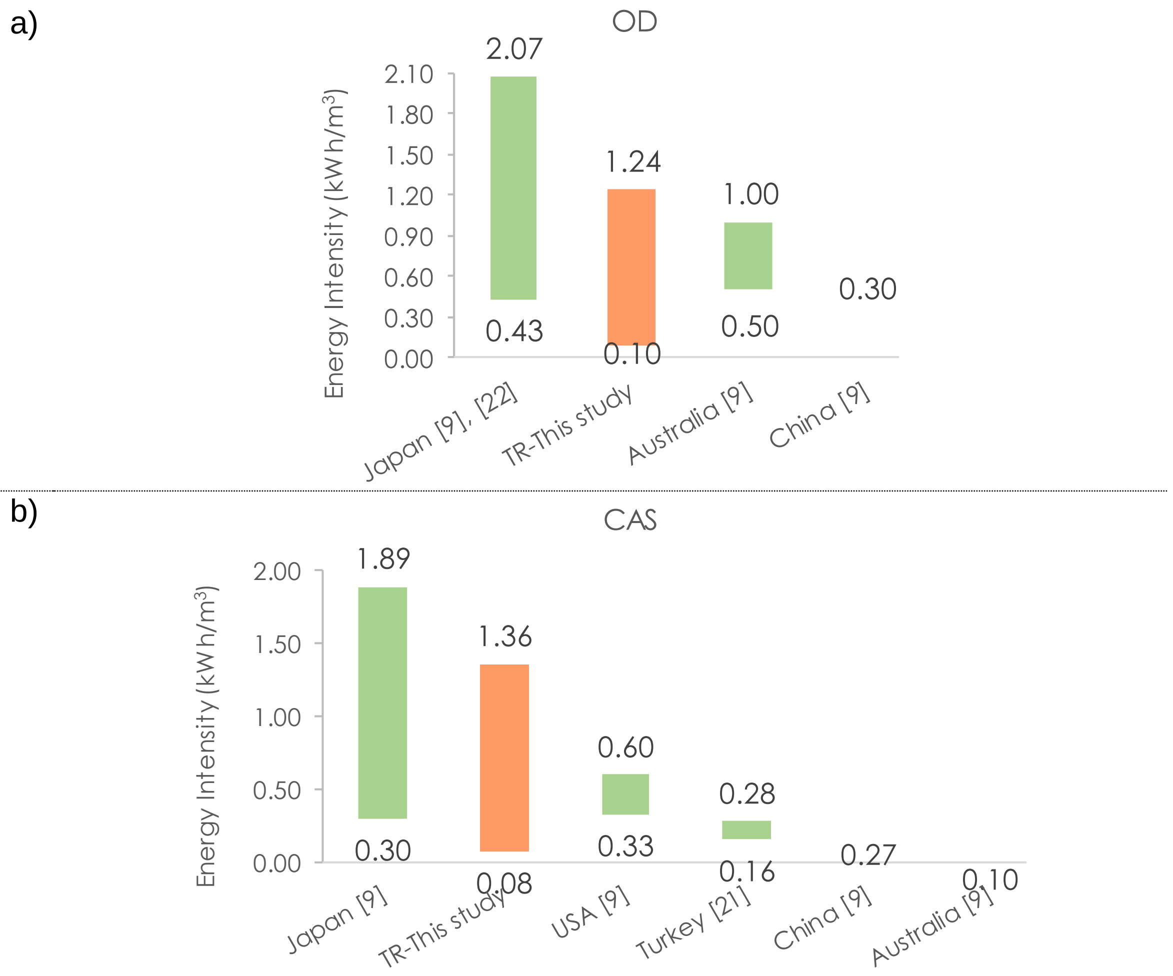


Figure 4.25. Comparison of Turkey's energy intensity for a) OD treatment b) CAS treatment (adapted from [9], [22], [26])

The deviation range for MBR in Turkey is so small because of the sample size. There are only 2 data points using MBR in the available data set. Their values are close to each other and around 0.35 kWh/m^3 within the ranges from 0.10 to 1.60 for different countries found in the literature [9], [23].

To investigate the energy intensity in detailed based on not only the type/process but also flow rate of the WWTPs, an approach of combining two of them was used as the relation between the amount of flow rate and the energy intensity was revealed in various studies [21], [24], [26]. Table 4.2 presents the median values of energy intensities of the available data based on the flow rate and process category. As can be seen in the table, energy intensity generally tends to decrease as the amount of treated wastewater increases especially for the ones except natural and package treatments. This table could give a general idea on the behavior of energy intensity of the plants however, the values may vary from plant to plant due to the factors that are implicated in the previous sections.

Table 4.2. Median values of energy intensity (kWh/m^3) by process and treated wastewater (m^3/y)

Flow rate (m^3/y)	Energy Intensity – EI (kWh/m^3)								
		Secondary			Advanced				
	Natural	Package	CAS	EAAS	A2O	Bardenpho	CAS + N, P	EAAS + N, P	SBR + N, P
0 - 200k	0.335	0.376	0.630	0.885	-	-	-	0.640	-
200k - 500k	-	0.514	0.442	0.387	-	-	-	0.474	-
500k - 1m	-	0.792	0.589	0.510	-	-	0.662	0.517	0.333
1m - 10m	0.113	0.347	0.275	0.428	-	0.553	0.485	0.386	-
10m - 50m	0.099	0.549	0.246	0.311	-	0.417	0.353	0.170	-
50m - 100m	0.066	-	0.221	-	0.518	0.389	-	0.283	-
100m - 150m	-	-	0.136	-	0.317	-	0.364	-	-
150m - 200m	0.117	-	-	-	-	-	-	-	-
200m - 300m	0.106	-	0.115	-	-	-	-	-	-

The total electricity consumptions of WWTPs of which data were missing, were calculated by using equation 3.7, and Table 4.2 for the $EI_{category}$ parameter in the equation. To test this approach, electricity intensities of the known 240 points were selected based on Table 4.2. The median of the absolute error margins between the real EIs and the EIs estimated by Table 4.2 was calculated as 25% whereas the error margin basically ranges between -13% and 0% for 52 of the WWTPs (see Figure 4.26). In addition, the absolute error margin is less than 25% for 54% of the data.

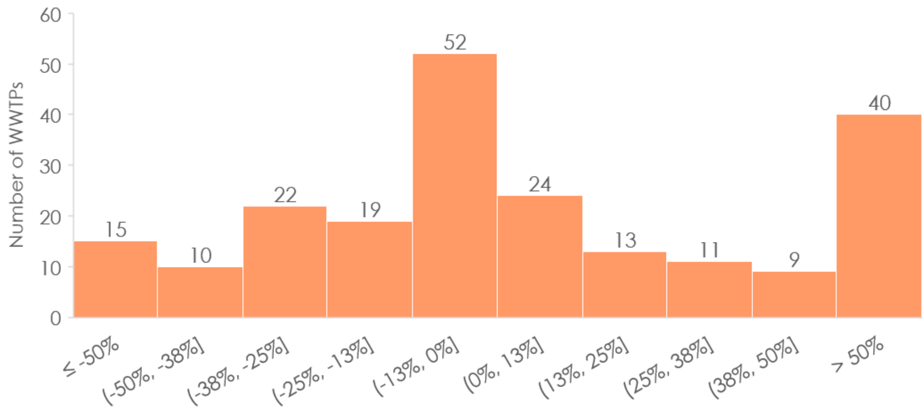


Figure 4.26. Error margins of the estimated energy intensities (kWh/m^3)

As Figure 4.26 shows a positive skewness, majority of the WWTPs deviating from median have a higher energy consumption per flow rate. Therefore, it could be concluded that those WWTPs have a potential of energy efficiency implementations.

4.4 Analysis of Renewable Energy Integration to WWTPs

Before using the simulation model for evaluation of the RES integration, the assumptions were verified by using 12 WWTPs having the most complete data. To this end, available biomass and gasification ratio of the plants were calculated respectively with equation 3.1 and equation 3.4 given in Section 3.1.2.1. The needed parameters (see Section 3.1.2) were filled in the related fields in the HOMER software as explained in Section 3.3. The simulated systems have only a biogas generator in addition to the grid to check whether the system can generate a close amount of electricity to the real amount of generation. The real and simulation results of the selected WWTPs were given in Table 4.3.

Table 4.3. Specifications of the selected wastewater treatment plants for validation

WWTP	Real Case			Simulation Result			Error Margin (%)
	EC[a] (MWh/y)	EP[b] (MWh/y)	REP[c] share (%)	EC[a] (MWh/y)	EP[b] (MWh/y)	REP[c] share (%)	
1.	26,235	2,338	8.9	26,235	2,190	8.3	-6
2.	17,339	9,497	54.8	17,339	9,636	55.5	1
3.	29,332	3,252	11.1	29,332	3,066	10.5	-6
4.	15,560	10,475	67.3	15,560	10,950	69.7	5
5.	7,654	3,805	49.7	7,654	3,942	51.4	4
6.	1,876	739	39.4	1,876	657	35.0	-11
7.	6,745	3,878	57.5	6,744	3,942	58.3	2

WWTP	Real Case			Simulation Result			Error Margin (%)
	EC[a] (MWh/y)	EP[b] (MWh/y)	REP[c] share (%)	EC[a] (MWh/y)	EP[b] (MWh/y)	REP[c] share (%)	
8.	7,187	3,751	52.2	7,187	4,137	50.5	10
9.	15,907	8,651	54.4	15,907	8,760	55.0	1
10.	14,909	2,772	18.6	14,910	2,628	17.6	-5
11.	16,180	4,529	28.0	16,179	4,544	26.7	0
12.	7,821	3,028	38.7	7,821	3,242	36.7	7

[a] Electricity consumption, [b] Electricity production, [c] Renewable energy production

According to the results, the systems were feasible and could generate a close amount of electricity to the real amounts with an absolute error margin range of 1% and 11% (see Figure 4.27). In addition, the real error margins do not tend to be all positive or negative indicating that the variation is normal. However, HOMER did not offer these production amounts as a solution because it searches for the optimum solution which meets the electricity load with the lowest net present cost. Still, it confirms that the real amount of electricity can be generated with the assumptions made within this study.

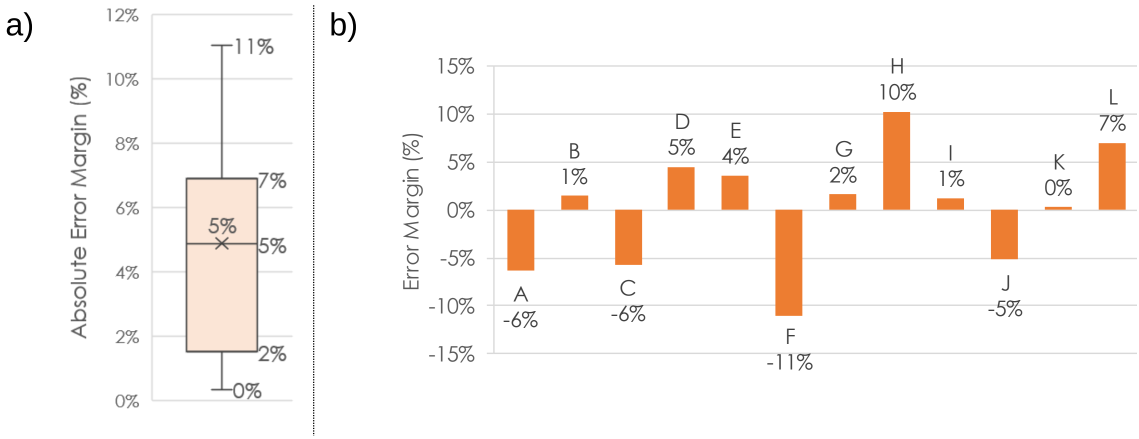


Figure 4.27. a) Absolute error margins for generated electricity with HOMER in 12 WWTPs b) Real error margins for generated electricity with HOMER in 12 WWTPs

The sizes of the biogas generators used in these 12 WWTPs were found for 11 of them to compare the sizes used in HOMER. The sizes used in the HOMER are generally 40% less than the currently used size. This is attributable to not only the high number of assumptions in this study but also being some of the generator sizes given for the WWTPs are the installed capacity instead of the utilized capacity.

Following the verification of the assumptions made, the WWTPs with the electricity consumption and annual flow rate data were examined for the simulation. As a result, the total number of eligible data which have the energy intensity and gasification ratio while does not have electricity production from biogas is 123. From these, 25 WWTPs were selected by ensuring that the sample represents various regions of Turkey, different type of treatment and amount of treated wastewater. 60% of the selected WWTPs employs advanced treatment while the rest employs secondary treatment. The distribution of the selected WWTPs based on the annual flow rate together with the 123 eligible data is shown in Figure 4.28

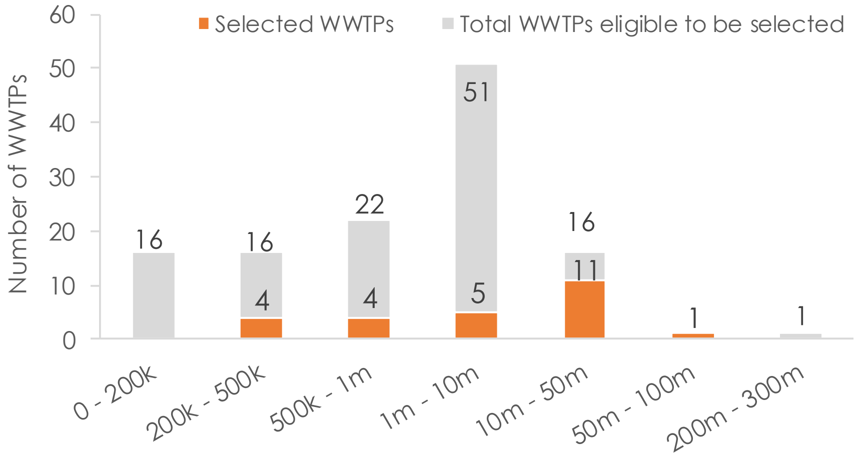


Figure 4.28. The distribution of the annual flow rate of the selected and the total eligible WWTPs

As indicated before, the system was simulated on a scenario basis with the parameters of CO_2 emissions penalty, and the electricity selling price (see Table 4.4). The base case is using only grid for each scenario option.

Table 4.4. Used scenarios within the simulations

Parameters/Scenario	A	B	C	D	E	F
Electricity Selling Price ($/kWh)	0.000	0.000	0.050	0.050	0.133	0.133
CO_2 Emissions Penalty ($/t)	0.000	16.000	0.000	16.000	0.000	16.000

The comparison of the scenarios is given based on the main scenario of electricity selling price in Table 4.5, Table 4.6 and Table 4.7.

Table 4.5. Simulation results for no electricty selling (Scenario A & B)

WWTP	TWW class	Type	Input			Scenario A (CO_2 penalty: 0 $/t)					Scenario B (CO_2 penalty: 16 $/t)				
			EC (MWh/y)	Gasification (kg biogas/ kg biomass)	Biomass (t/day)	EP_{gen} (MWh/y)	EP_{pv} (MWh/y)	RE share in supply (%)	Payback Period (Years)	CO_2 Emissions (t/y)	EP_{gen} (MWh/y)	EP_{pv} (MWh/y)	RE share in supply (%)	Payback Period (Years)	CO_2 Emissions (t/y)
1.	6	III.	41,226	67.43	0.18	0	5,450	12	14	17,500	16,400	5,450	52	12	9,577
2.	5	II.	6,693	19.47	0.08	0	1,424	19	15	2,614	0	1,600	22	13	2,552
3.	5	II.	10,300	12.83	0.11	0	2,200	20	15	4,019	0	2,486	22	13	3,918
4.	5	II.	5,119	13.92	0.11	0	1,085	19	15	2,001	0	1,218	22	13	1,954
5.	5	III.	4,137	13.05	0.19	0	0	0	0	1,997	1,774	882	62	13	761
6.	5	III.	10,383	29.15	0.10	0	2,230	20	15	4,048	0	2,459	21	13	3,966
7.	5	III.	7,098	21.75	0.19	0	1,442	19	15	2,801	3,404	1,442	66	14	1,161
8.	5	III.	13,035	28.28	0.14	0	3,069	21	14	4,976	0	3,370	23	13	4,876
9.	5	III.	4,891	3.48	0.19	0	1,523	28	12	1,730	0	1,609	29	11	1,706
10.	5	III.	9,207	10.88	0.19	0	2,443	24	13	3,413	1,875	2,571	45	12	2,469
11.	5	III.	5,766	10.44	0.19	0	1,499	24	13	2,147	1,783	1,587	55	12	1,261
12.	5	II.	1,378	13.05	0.19	0	0	0	0	665	0	0	0	0	665
13.	4	II.	3,052	5.18	0.19	0	0	0	0	1,473	1,392	0	46	8	804
14.	4	III.	2,146	6.53	0.22	0	0	0	0	1,036	1,526	0	71	7	301
15.	4	III.	436	1.13	0.12	0	0	0	0	210	0	0	0	0	210
16.	4	III.	2,406	4.79	0.15	0	0	0	0	1,162	0	0	0	0	1,162
17.	4	II.	2,089	3.18	0.19	0	0	0	0	1,009	0	0	0	0	1,009
18.	3	II.	799	0.69	0.14	0	0	0	0	386	0	0	0	0	386
19.	3	III.	505	0.52	0.17	0	0	0	0	244	0	0	0	0	244
20.	3	III.	675	1.09	0.17	0	0	0	0	326	0	0	0	0	326
21.	3	II.	570	1.09	0.17	0	0	0	0	275	0	0	0	0	275
22.	2	II.	180	0.17	0.15	0	0	0	0	87	0	0	0	0	87
23.	2	III.	142	0.25	0.15	0	0	0	0	68	0	0	0	0	68
24.	2	III.	227	0.87	0.06	0	0	0	0	109	0	0	0	0	109
25.	2	II.	82	0.13	0.15	0	0	0	0	40	0	0	0	0	40

II: Secondary; III: Advanced; 1: 0 - 200k m^3/y;2: 200k - 500k m^3/y; 3: 500k - 1m m^3/y; 4: 1m - 10m m^3/y; 5: 10m - 50m m^3/y; 6: 50m - 100m m^3/y

Table 4.6. Simulation results for the electricty selling price is 0.05 $/kWh (Scenario C & D)

WWTP	TWW class	Type	Input			Scenario C (CO_2 penalty: 0 $/t)					Scenario D (CO_2 penalty: 16 $/t)				
			EC (MWh/y)	Gasification (kg biogas/ kg biomass)	Biomass (t/day)	EP_{gen} (MWh/y)	EP_{pv} (MWh/y)	RE share in supply (%)	Payback Period (Years)	CO_2 Emissions (t/y)	EP_{gen} (MWh/y)	EP_{pv} (MWh/y)	RE share in supply (%)	Payback Period (Years)	CO_2 Emissions (t/y)
1.	6	III.	41,226	67.43	0.18	0	5,450	12	14	17,500	16,500	5,450	52	12	9,555
2.	5	II.	6,693	19.47	0.08	0	1,857	25	15	2,470	0	2,132	28	14	2,400
3.	5	II.	10,300	12.83	0.11	0	2,858	25	15	3,800	0	3,315	28	14	3,685
4.	5	II.	5,119	13.92	0.11	0	1,413	25	15	1,891	0	1,656	29	14	1,829
5.	5	III.	4,137	13.05	0.19	0	1,153	25	15	1,525	1,678	1,199	66	14	707
6.	5	III.	10,383	29.15	0.10	0	2,916	25	15	3,821	0	3,374	29	14	3,707
7.	5	III.	7,098	21.75	0.19	0	1,803	23	15	2,673	3,276	1,914	70	14	1,069
8.	5	III.	13,035	28.28	0.14	0	4,240	29	14	4,633	0	4,814	32	13	4,517
9.	5	III.	4,891	3.48	0.19	0	3,600	52	13	1,459	0	4,151	56	13	1,430
10.	5	III.	9,207	10.88	0.19	0	3,664	34	13	3,113	2,924	4,210	67	14	1,625
11.	5	III.	5,766	10.44	0.19	0	2,283	34	13	1,952	1,614	2,444	62	13	1,150
12.	5	II.	1,378	13.05	0.19	0	0	0	0	665	0	0	0	0	665
13.	4	II.	3,052	5.18	0.19	0	1,443	39	13	994	1,301	1,544	79	14	358
14.	4	III.	2,146	6.53	0.22	0	1,099	42	13	687	1,083	1,081	84	11	193
15.	4	III.	436	1.13	0.12	0	0	0	0	210	0	0	0	0	210
16.	4	III.	2,406	4.79	0.15	0	789	29	14	854	0	892	32	13	833
17.	4	II.	2,089	3.18	0.19	666	839	64	16	387	0	964	38	13	686
18.	3	II.	799	0.69	0.14	0	0	0	0	386	0	0	0	0	386
19.	3	III.	505	0.52	0.17	0	0	0	0	244	0	0	0	0	244
20.	3	III.	675	1.09	0.17	0	0	0	0	326	0	0	0	0	326
21.	3	II.	570	1.09	0.17	0	0	0	0	275	0	0	0	0	275
22.	2	II.	180	0.17	0.15	0	0	0	0	87	0	0	0	0	87
23.	2	III.	142	0.25	0.15	0	0	0	0	68	0	0	0	0	68
24.	2	III.	227	0.87	0.06	0	0	0	0	109	0	0	0	0	109
25.	2	II.	82	0.13	0.15	0	0	0	0	40	0	0	0	0	40

II: Secondary; III: Advanced; 1: 0 - 200k m^3/y;2: 200k - 500k m^3/y; 3: 500k - 1m m^3/y; 4: 1m - 10m m^3/y; 5: 10m - 50m m^3/y; 6: 50m - 100m m^3/y

Table 4.7. Simulation results for the electricty selling price is 0.133 $/kWh (Scenario E & F)

WWTP	TWW class	Type	Input			Scenario E (CO_2 penalty: 0 $/t)					Scenario F (CO_2 penalty: 16 $/t)				
			EC (MWh/y)	Gasification (kg biogas/ kg biomass)	Biomass (t/day)	EP_{gen} (MWh/y)	EP_{pv} (MWh/y)	RE share in supply (%)	Payback Period (Years)	CO_2 Emissions (t/y)	EP_{gen} (MWh/y)	EP_{pv} (MWh/y)	RE share in supply (%)	Payback Period (Years)	CO_2 Emissions (t/y)
1.	6	III.	41,226	67.43	0.18	15,100	5,450	44	12	12,200	17,200	5,450	53	13	9,485
2.	5	II.	6,693	19.47	0.08	0	5,485	55	10	2,037	0	5,485	55	10	2,037
3.	5	II.	10,300	12.83	0.11	1,852	5,487	51	12	3,283	1,847	5,487	50	11	3,286
4.	5	II.	5,119	13.92	0.11	1,787	5,483	70	9	1,436	1,774	5,483	70	9	1,440
5.	5	III.	4,137	13.05	0.19	3,490	5,487	93	9	316	3,490	5,487	93	9	316
6.	5	III.	10,383	29.15	0.10	3,796	5,490	57	12	3,194	3,675	5,490	57	11	3,224
7.	5	III.	7,098	21.75	0.19	5,805	5,325	82	9	1,117	5,837	5,325	91	9	517
8.	5	III.	13,035	28.28	0.14	4,513	5,777	56	10	3,774	4,673	5,777	57	9	3,709
9.	5	III.	4,891	3.48	0.19	931	7,053	77	7	1,082	931	7,053	77	7	1,082
10.	5	III.	9,207	10.88	0.19	2,190	6,171	65	9	2,084	2,190	6,171	65	8	2,084
11.	5	III.	5,766	10.44	0.19	2,190	6,174	80	8	981	2,190	6,174	80	8	981
12.	5	II.	1,378	13.05	0.19	3,458	4,650	95	7	185	3,458	4,686	100	8	6
13.	4	II.	3,052	5.18	0.19	1,376	6,449	88	7	461	1,376	6,449	88	7	461
14.	4	III.	2,146	6.53	0.22	2,023	6,596	93	7	289	2,023	6,596	93	7	289
15.	4	III.	436	1.13	0.12	0	0	0	0	210	0	0	0	0	210
16.	4	III.	2,406	4.79	0.15	1,012	5,770	84	8	554	1,013	5,770	84	8	539
17.	4	II.	2,089	3.18	0.19	848	6,153	89	8	356	847	6,153	89	8	352
18.	3	II.	799	0.69	0.14	0	0	0	0	386	0	0	0	0	386
19.	3	III.	505	0.52	0.17	0	0	0	0	244	0	0	0	0	244
20.	3	III.	675	1.09	0.17	0	0	0	0	326	0	0	0	0	326
21.	3	II.	570	1.09	0.17	0	0	0	0	275	0	0	0	0	275
22.	2	II.	180	0.17	0.15	0	0	0	0	87	0	0	0	0	87
23.	2	III.	142	0.25	0.15	0	0	0	0	68	0	0	0	0	68
24.	2	III.	227	0.87	0.06	0	0	0	0	109	0	0	0	0	109
25.	2	II.	82	0.13	0.15	0	0	0	0	40	0	0	0	0	40

II: Secondary; III: Advanced; 1: 0 - 200k m^3/y;2: 200k - 500k m^3/y; 3: 500k - 1m m^3/y; 4: 1m - 10m m^3/y; 5: 10m - 50m m^3/y; 6: 50m - 100m m^3/y

An important conclusion of the simulation results is that the integration of RESs is not cost effective for the WWTPs for those with a flow rate of less than 1 M m^3/year under the selected scenarios while IEA indicated that this limit is 1.8 M m^3/year in theory and 8 M m^3/year in practice [3]. The integration is not economically preferable for eight of the selected WWTPs (see Table 4.5, Table 4.6 and Table 4.7) under any of the scenarios as the capacity decreases, the available biomass and the energy demand also decreases. Nevertheless, only the optimal solutions are presented in this study while there are solutions that are feasible but not cost effective. As it can be clearly seen in Figure 4.29, unlike PV, biogas is a cost-effective option for only in large scale plants.

Another important conclusion is the impact of the electricity selling price, especially on biogas power. In case of no selling or even a selling price of 0.05 $/kWh, biogas power integration is not cost-effective for any of the flow rates, while PV still could be utilized in small-scales (see Table 4.5, Table 4.6). As the electricity selling price increases, the renewable energy production over energy demand increases (see Figure 4.29).

a)

b)

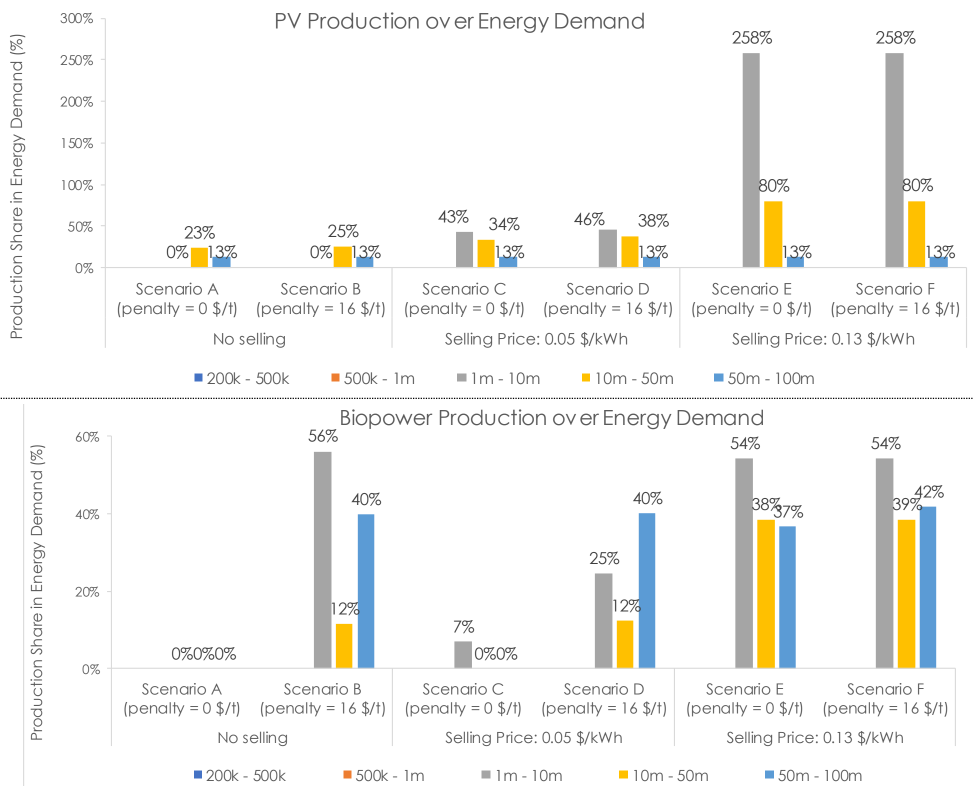


Figure 4.29. a) Electricity production from PV over electricity demand b) Electricity production from biogas over electricity demand

The electricity selling price impacts the electricity utilization as well. The plants tend to produce more electricity than their demand in order to sell the excess to the grid and get revenue. Even though the utilization of the generated electricity inside the plant increases, the difference between the produced and utilized electricity inside the plant also increases significantly (see Figure 4.30).

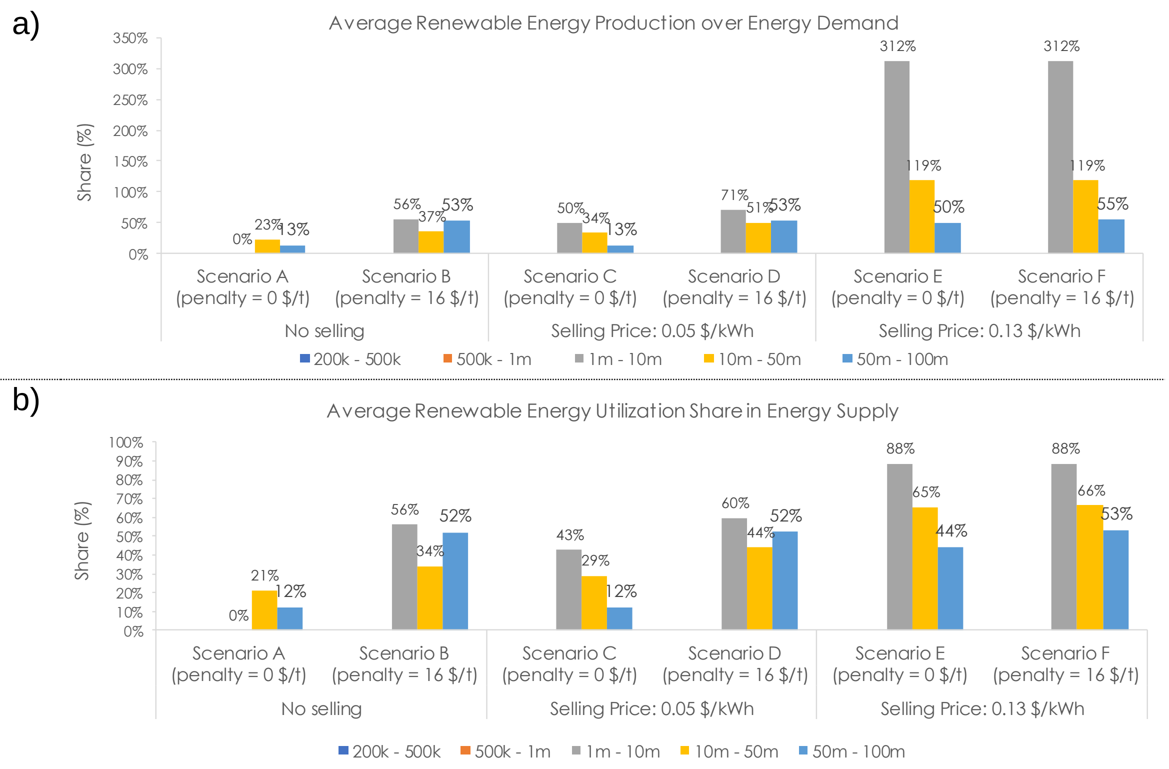


Figure 4.30. a) Renewable energy production over electricity demand b) Utilization of the renewable energy to meet the energy demand

Furthermore, its clearly seen that the penalty for CO_2 emissions has a significant effect on the choice of PV and biogas integration. It causes WWTPs to integrate biogas and PV especially for the cases of “no selling” and “a selling price of 0.05 $/kWh” (see Table 4.5, Table 4.6, Table 4.7 and Figure 4.29).

For all the flow rates, an increasing trend in total renewable energy production share can be seen (see Figure 4.31). For the scenario C, however, a decrease is obvious despite the increase from scenario A. This is due to the selling price of 0.05 $/kWh on its own is not still as good as CO_2 penalty to incentivize the renewable energy integration and utilization, especially for the WWTPs with an annual flow rate of more than 50 million m^3.

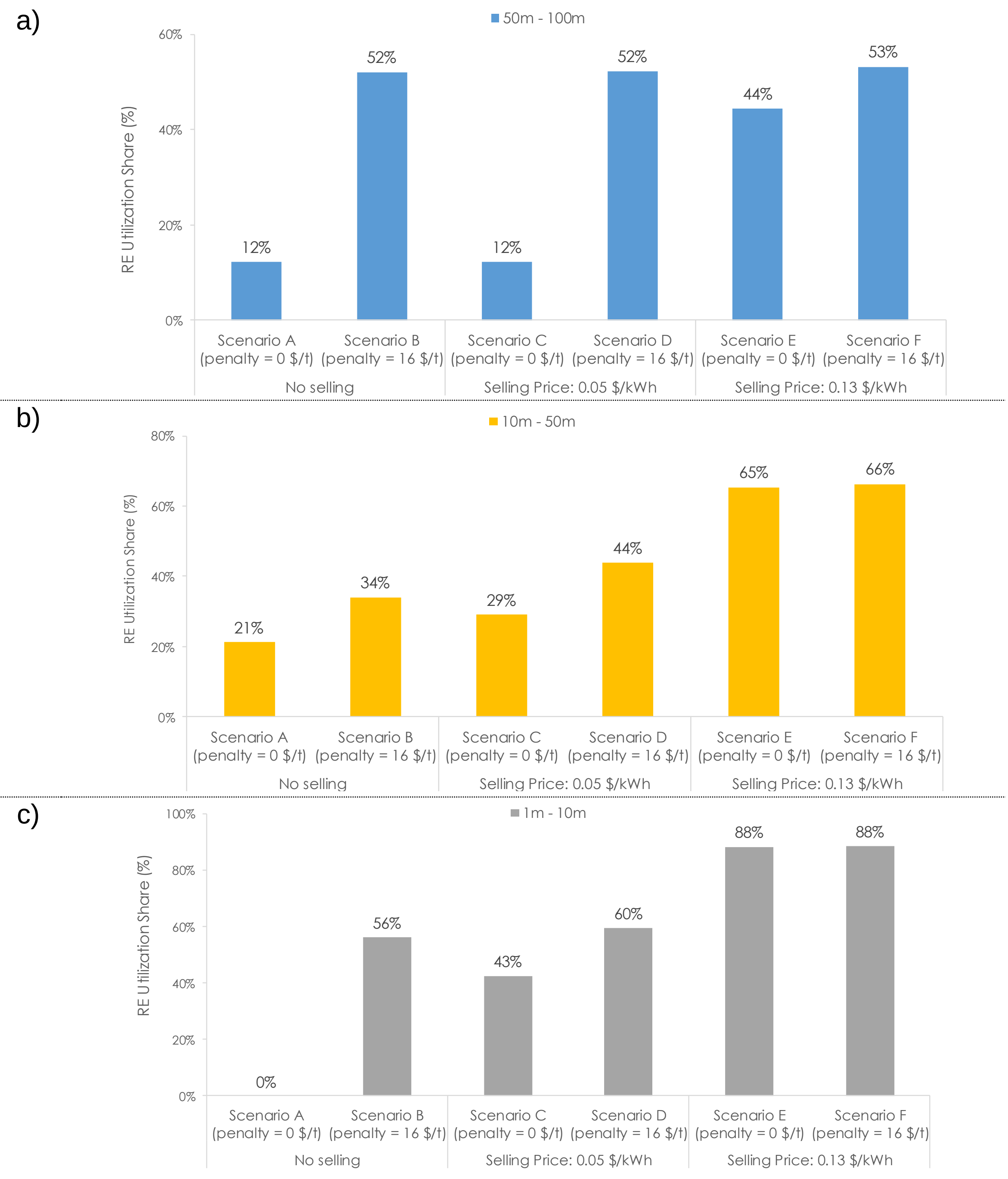


Figure 4.31. a) Renewable energy production share in WWTPs with an annual flow rate of 50 m – 100 m b) Renewable energy production share in WWTPs with an annual flow rate of 10 m – 50 m c) Renewable energy production share in WWTPs with an annual flow rate of 1 m – 10 m

The payback periods of the systems show a trend of decline through the increase of electricity selling price (see Figure 4.32). As revealed earlier in Figure 4.30, WWTPs tends to gain higher revenue with a renewable energy production of much higher than their energy demand in case of an increased electricity selling price.

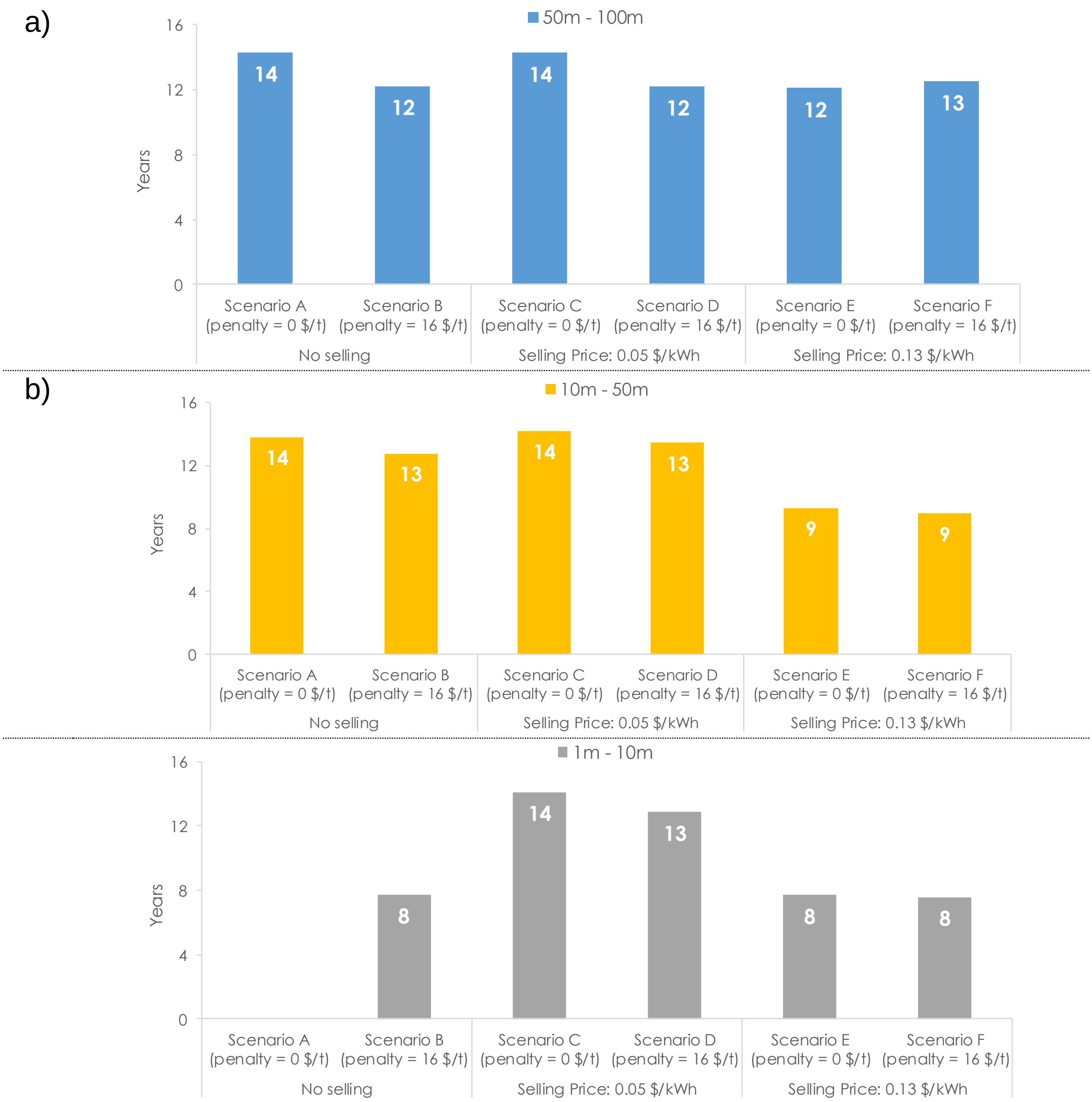


Figure 4.32. a) Payback periods for WWTPs with an annual flow rate of 50 m - 100 m b) Payback periods for WWTPs with an annual flow rate of 10 m - 50 m c) Payback periods for WWTPs with an annual flow rate of 1 m - 10 m

In parallel with the renewable energy integration, the CO_2 emission reductions compared to base case in each scenario follow growing trends (see Figure 4.33). In scenario F, the reduction potential could reach up to 62% for 1-10 M m^3 sized WWTPs. According to the scenario outcomes, as a result of the implementation of the optimum solutions to the WWTPs, the total emissions of the 25 WWTPs could dropped to 32 kt CO_2 from 64 kt CO_2 (see Figure 4.33).

Figure 4.33. a) The CO_2 emission reduction potential for each flow rate in each scenario b) The total CO_2 emissions for each scenario

4.5 Concluding Remarks

In this chapter, the results of the conducted researches to analyze the energy intensity (kWh/y) of WWTPs in Turkey and the integration of RES, *i.e.* PV and biogas, into WWTPs were presented and explained in detail.

With the survey conducted for collecting data from WWTPs operators, it was revealed that the aeration process of the WWTPs in Turkey is responsible with about 40% of the plant's electricity consumption. This value is in line with the literature data for different WWTPs around the world [16], [19], [21], [23], [25], [105], [106].

According to the perception part of the survey, WWTPs operators believe that PV and anaerobic digestion will be the first two renewable energy technologies in 10 years even though PV is also currently in the first line according to the participants' responses. As a second important observation of the second part of the survey is the main barrier for RES integration to WWTPs is financial.

As a result of the data collection process of the study (see Section 3.1) data of 456 WWTPs were achieved. It was found that the total electricity consumption has a strong correlation of 68% with flow rate, as even higher correlation values observed in various studies [24], [25], [27], [106].

After cleansing and analyzing of the data set, the energy intensity of WWTPs in Turkey was determined for both overall and type/processes. Analysis shows that the overall energy intensity of Turkey is between 0.07 and 1.34 kWh/m^3. EI is found to be higher or lower values than the values reported in this study [19], [24].

Another conclusion of the energy intensity calculation is that the secondary treatment has higher energy intensity than advanced treatment likewise the literature data [9], [21]. Type/process-based comparison concluded an interesting result that the energy intensities of CAS and EAAS processes are close to each other, especially in terms of their median values. Even though it was expected that EAAS should have higher values because of its longer duration of aeration need [9], [21], [22], [24], the maximum value that is observed for EAAS is lower than the one for CAS.

Finally, the energy intensities grouped by flow rates of the WWTPs and used the median values for determination of the energy intensities. The error margin of the real energy intensity values is calculated to test this approach. As it is observed that the majority of the error margins tends to be positive, electricity consumption per treated wastewater is higher in most of the WWTPs and this creates an area for energy efficiency applications.

The final research of this study is the assessment of the PV and biogas integration to WWTPs. For this assessment, 25 WWTPs representing various sizes and with available data were selected and their plant specific values together with the other assumed values were input to the simulation software HOMER. The scenarios based on electricity selling price and CO_2 emissions penalty (see Table 4.4) were also identified to HOMER. As HOMER searches for a result with minimum net present value (NPV) to meet the electricity demand of the system, the optimum solutions for each scenario was analyzed within the scope of this study although

HOMER documents all feasible solutions that could be considered. The summary of the results was given in Table 4.8.

Table 4.8. Summary table of the simulation results in terms of impact of the scenarios

	Scenarios					
200k - 500k m^3/y	A	B	C	D	E	F
Average Payback Period (y)	N/A	N/A	N/A	N/A	N/A	N/A
Average RE Utilization (%/y)	0%	0%	0%	0%	0%	0%
Average RE Production (%/y)	0%	0%	0%	0%	0%	0%
Average PV Production* (%/y)	0%	0%	0%	0%	0%	0%
Average Bioenergy Production* (%/y)	0%	0%	0%	0%	0%	0%
Average CO_2 Saving (%/y)	0%	0%	0%	0%	0%	0%
500k - 1m m^3/y	A	B	C	D	E	F
Average Payback Period (y)	N/A	N/A	N/A	N/A	N/A	N/A
Average RE Utilization (%/y)	0%	0%	0%	0%	0%	0%
Average RE Production (%/y)	0%	0%	0%	0%	0%	0%
Average PV Production* (%/y)	0%	0%	0%	0%	0%	0%
Average Bioenergy Production* (%/y)	0%	0%	0%	0%	0%	0%
Average CO_2 Saving (%/y)	0%	0%	0%	0%	0%	0%
1m - 10m m^3/y	A	B	C	D	E	F
Average Payback Period (y)	N/A	8	14	13	8	8
Average RE Utilization (%/y)	0%	56%	43%	60%	88%	88%
Average RE Production (%/y)	0%	56%	50%	71%	312%	312%
Average PV Production* (%/y)	0%	0%	43%	46%	258%	258%
Average Bioenergy Production* (%/y)	0%	56%	7%	25%	54%	54%
Average CO_2 Saving (%/y)	0%	-29%	-36%	-53%	-62%	-62%
10m - 50m m^3/y	A	B	C	D	E	F
Average Payback Period (y)	14	13	14	13	9	9
Average RE Utilization (%/y)	21%	34%	29%	44%	65%	66%
Average RE Production (%/y)	23%	37%	34%	51%	119%	119%
Average PV Production* (%/y)	23%	25%	34%	38%	80%	80%
Average Bioenergy Production* (%/y)	0%	12%	0%	12%	38%	39%
Average CO_2 Saving (%/y)	-19%	-33%	-26%	-40%	-48%	-50%
50m - 100m m^3/y	A	B	C	D	E	F
Average Payback Period (y)	14	12	14	12	12	13
Average RE Utilization (%/y)	12%	52%	12%	52%	44%	53%
Average RE Production (%/y)	13%	53%	13%	53%	50%	55%
Average PV Production* (%/y)	13%	13%	13%	13%	13%	13%
Average Bioenergy Production* (%/y)	0%	40%	0%	40%	37%	42%
Average CO_2 Saving (%/y)	-12%	-52%	-12%	-52%	-39%	-52%

*Average PV/Bioenergy Production is the production over energy demand as percentage.

An important finding of the simulation results is that any of PV and biogas integration is not cost effective for WWTPs with an annual flow rate less than 1 million m^3 (see Table 4.8). For the ones that has a flow rate between 1 million and 10 million m^3/y, an incentive like electricity selling price or a fine like CO_2 emissions penalty are needed for supporting. Otherwise using the electricity from the grid is cheaper for them.

The increase of the electricity selling prices motivates WWTPs for the integration of RES. An electricity selling price of 0.05 $/kWh is not as stimulating as the CO_2 penalty as seen in the Scenarios A, B, and C. On the other hand, a high electricity selling price of 0.133 $/kWh is supportive for the integration of RES mainly for selling the electricity produced instead of excess. As it can be seen in Table 4.8 thanks to the electricity selling price, the payback period is much less than the first four scenarios in scenarios F and D.

Finally, even in the scenario A where no economic incentive or penalty is defined in the system, there is a potential of CO_2 emissions reduction of 15%. It could be increase up to 51% with right political and economic instruments.

5 CONCLUSION AND RECOMMENDATION

Water and energy are one of the basic needs that create a nexus for people to have welfare. While it is hard to live in scarce of any of them, it is also hard to obtain one them without the other one. An amount of electricity as much as the Australia's energy consumption is consumed by the water sector globally while its 60% is attributable to electricity consumption [3]. It was estimated that the water sector in Turkey consumes 2-5% of the total electricity consumption like in the world [3], [5]. Consequently, the water sector, especially wastewater treatment is one of the contributors to GHG emissions [13], [14], since a large share of energy costs of a municipality is caused by the WWTPs [3]. In Turkey, there are also examples of municipalities of which WWTPs causing 86% of GHG emissions of the WSA [15] and 20-40% of the operational costs due to electricity utilization [17].

In this thesis, the economic and environmental impacts of integrating PV and biogas to WWTPs were analyzed due to the high energy demand and high energy potential of wastewater sector in Turkey. To do this, the energy intensity of the WWTPs in Turkey was investigated as a first step. The literature research on determination on energy intensity gave an idea on various methods for calculation of the energy intensity as well as the values. The general approach is calculating the energy intensity based on flow rate (m^3/y) nevertheless there are also benchmarks for per BOD removed or per capita. It was concluded that the approach depends on the aim of the study. Since there are variations in energy intensity figures even in the same country and the same type of treatments, it was concluded that a country specific research and various modelling approaches should have been used to determine the energy intensities for Turkey.

As the Turkey and the WWTPs have a big potential of solar energy and bioenergy, different RES employment examples both theoretical and practical were examined through a literature research to reveal the possible impacts of RES integration. It was concluded that RES integration has a significant economic and environmental opportunity for WWTPs such as providing the plant's energy demand by RES with a range of 2.5 to 100 and even make a WWTP to gain revenue by reaching up to more than 100% renewable energy production.

In order to complete the task defined within this study, the study focused on 30 metropolitan municipalities representing 77% of the total population and 85-89% of the discharged/treated wastewater in Turkey. Data regarding energy consumption and other specifications of WWTPs of 30 metropolitan municipalities was collected through basically open literature and completed the data caps through online survey, and private communication.

The survey focused on two main points; first is the energy consumption of the WWTP and the second one is the perception of the WWTPs operators on integration of RES to their plant. As a result of the first part of the survey, it was revealed that the aeration is the first energy consumer with a share of 40% of the total energy consumption in the WWTPs supporting the findings in the literature [16], [19], [21], [23], [25], [105], [106]. The second part highlighted the PV and biogas technologies as first and second one in 10 years. In addition, the participants indicated that the main reason for not using RES in the WWTPs is financial barriers.

With the open literature 481 WWTP's main data has been achieved. With private communication most of the data of 456 of them were able to be completed. By analyzing the relationship between the total energy consumption and the BOD and flow rate, the R^2 was found as 69% and 68% respectively lower than the observed values of 85-95% found in the literature [24], [25], [27], [106].

The energy intensity was calculated with the available data set and the resulted values were trimmed out by the outliers. Resulting 431 WWTP were analyzed to calculate the energy intensity of Turkey.

The overall energy intensity of Turkey ranges from 0.07 to 1.36 kWh/m^3. In some other countries, the variation is much higher; *e.g.* from 0.13 to 3.14 kWh/m^3 for Spain and from 0.05 to 5.50 kWh/m^3 for Germany [19], [24]. The secondary treatment has higher energy intensity range from 0.08 to 1.36 kWh/m^3 than the range of advanced one from 0.15 to 0.99 kWh/m^3 [9], [21]. Their median values on the other hand are close to each other. When advanced treatment compared with other countries, Turkey has a wider range than Poland (0.48-0.87 kWh/m^3) while narrower range than Japan (0.39-3.74 kWh/m^3) and Australia (0.13-10.55 kWh/m^3) [9], [23], [26].

The process-based analyze of the energy intensity revealed that the CAS has the highest energy intensity among other processes despite the fact that the EI for EAAS is higher in most of the studies [9], [21], [22], [24]. CAS has a range of 0.08-1.36 kWh/m^3, slightly lower than Japan (0.30-1.89 kWh/m^3) and higher than USA (0.33-0.60 kWh/m^3) [9].

The energy intensity data set was analyzed together with flow rate based on processes used in WWTPs. The known energy intensity values were compared with the median value of a process for a flow rate category. It was concluded that the real values deviating from the median have tendency to be on the positive side meaning that they are higher than the median values. This is an important area for an implementation of energy efficiency measures.

In order to assess the RES integration to WWTPs, HOMER software was used with the collected parameters (see Section 3.1.2). 25 WWTPs that is known as not an electricity producer, with the known PE and electricity consumption value and with following flow rates:

- 200k - 500k m^3/y
- 500k - 1m m^3/y
- 1m - 10m m^3/y
- 10m - 50m m^3/y
- 50m - 100m m^3/y

As indicated earlier, plant specific data and other parameters in addition to the scenario parameters *i.e.* electricity selling price and penalty for CO_2 emissions penalty were given to the system. HOMER Software is a strong tool to estimate not only the cost but also the environmental impacts of the simulated system on scenario basis by identifying the optimum solution with the NPV. Even though the HOMER gives other possible feasible combinations, the optimum combinations with the lowest NPV were compared within the scope of this study.

Highlighted conclusions from the scenario analysis are as follows:

- ✓ As HOMER gave an optimum combination for none of the scenarios for WWTPs having inflow rate less than 1m^3/y, RES integration is not cost-effective for the WWTP if not having an inflow rate higher than 1 million m^3 per year.
- ✓ Electricity selling price is a significant factor on the decision of RES integration as it impacts the possible amount of revenue and payback period, consequently the decision of the integration of RES.
- ✓ An emission penalty is an important policy instrument for the governments to accelerate the energy transition in the country.
- ✓ For all flow rates higher than 1 million m^3/y, electricity selling price inclusion to the system and introduction of a penalty for emissions are favorable to integrate RES.
- ✓ Utilization of the not only a penalty but also an incentive has the maximum positive impact as is observed scenario F.

This study was completed as a starting point however there are various areas that could be improved not only for this study but also to support any following ones:

- ✓ Detailed plant specific database is strongly needed for an overall and more accurate assessment for plants and countrywide.
- ✓ Even though this thesis was conducted with a large data set, it has also a large set of assumptions. Therefore, for the investment decisions, plant specific analysis is strongly recommended.
- ✓ As the observed positive skewness from the median values of the WWTPs, a detailed plant specific analysis is recommended to reveal the causes and implement energy efficiency measures in case of need.
- ✓ As it was observed from the results that the amount of increase in electricity selling price canalize the operators to utilize of RES more than its demand, the price selection should be analyzed further with more detailed and accurate models.
- ✓ The utilization of different market-based incentives and penalties should be analyzed and used together to ensure optimum economic and environmental impact because the CO_2 mitigation potential is increasing from 15% in a case like scenario A without any incentive or penalty to 51% in a case of both incentive and penalty.

- ✓ As HOMER Software searches for the option with the lowest net present value, some of the other feasible options would be considered by the plant operators.
- ✓ As found in the literature research that the hydraulic energy potential of WWTPs is another important source of energy that could be investigated in further studies.

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APPENDICES

Appendix A. Questionnaire

ATIKSU ARITMA TESİSLERİNİN ENERJİ TÜKETİMİ

ANKET FORMU

Bu anket, Hacettepe Üniversitesi Temiz Tükenmez Enerjiler Anabilim Dalı bünyesinde, Hacettepe Üniversitesi Çevre Mühendisliği Bölümü öğretim üyelerinden Doç. Dr. Merih Aydınalp Köksal'ın danışmanlığında gerçekleştirilen, Gözde Odabaş'ın yüksek lisans tez çalışması kapsamında hazırlanmıştır. Tez çalışmasının amacı; Türkiye'de tüm su ve atıksu işlemlerinde tüketilen enerjinin ortaya konularak azaltılması için tesislerde kullanılabilecek temiz-tükenmez enerji kaynaklarının belirlenmesidir. Tez çalışması kapsamında, biri Atıksu Arıtma Tesisleri; diğeri Su Arıtma Tesisleri ile olmak üzere iki anket yürütülecektir. Bu anketler ile, su ve atıksu tesislerinin mevcut enerji kaynakları, toplam ve proses bazlı enerji kullanımı ve gelecekteki potansiyel enerji kaynağı dağılımı üzerine temel veri ve görüşlerin toplanarak literatürden elde edilen verilerle karşılaştırmada kullanılması hedeflenmiştir.
Bu anketin yapılabilmesi için Hacettepe Üniversitesi Etik Komisyonu'ndan gerekli izin alınmıştır. Ankete katılım tamamen gönüllülük esasına dayalıdır. Anket, genel olarak kişisel rahatsızlık verecek sorular içermemektedir. Ancak, anket formunu doldururken sorulardan ya da herhangi başka bir nedenden ötürü kendinizi rahatsız hissederseniz cevaplama işini yarıda bırakabilirsiniz. Anket formunu doldurduktan sonra, anket yanıtlarınızın kullanılması konusunda fikrinizi değiştirirseniz tez danışmanı Doç. Dr. Merih Aydınalp Köksal'a ve/veya Gözde Odabaş'a aşağıda verilen iletişim kanalları aracılığıyla başvurmanız yeterli olacaktır. Bu durumda anket yanıtlarınız imha edilecektir.
Anket uygulanması için onay vermeden önce veya anket sırasında, çalışma hakkında merak ettiğiniz herhangi bir konuda tez öğrencisi Gözde Odabaş'tan detaylı bilgi alabilirsiniz. Anket sonrasında tez çalışması ile ilgili herhangi bir konuda detaylı bilgi almak isterseniz veya sorularınız var ise aşağıda iletişim bilgileri verilen tez danışmanı Doç. Dr. Merih Aydınalp Köksal'a ulaşabilirsiniz.

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Gizlilik:

- Ankette verilen tüm tekil yanıtlar ve yanıtların kimden temin edildiği gizli tutulacaktır.
- Anket yanıtları sadece tez öğrencisi ve danışmanı tarafından değerlendirilecek, bilimsel amaçlar doğrultusunda kullanılacak ve araştırmanın amacı dışında kullanılmayacaktır.
- Anket sonuçları, temel olarak veri karşılaştırması için kullanılacak olup, tekil olarak yer almayacak, toplulaştırılmış sonuçlar, tezde ve bilimsel yayınlarda kullanılacaktır.

Bu anket İçme Suyu Arıtma Tesislerine yönelik olup, aşağıdaki 6 bölümden ve çoğunluğu çoktan seçmeli olan 19 sorudan oluşmaktadır. Yaklaşık olarak 15-20 dk sürecektir.
1. Anket Bilgisi
2. İletişim Bilgisi (3 soru)
3. Kurumsal Bilgi (5 soru)
4. Tesisin Mevcut Ve Gelecekteki Enerji Kullanımı, Enerji Kaynağı Dağılımı (5 soru)
5. YEK konusundaki değerlendirmeniz (5 soru)
6. Son Sözler (Tercihen) (1 soru)

1. Anket Bilgisi

Dünya'nın enerji tüketiminin %2-%8'i su sektöründen kaynaklanmaktadır[1]. 2015'te Türkiye'nin toplam elektrik tüketimi 217.312 GWh iken Ankara, İstanbul ve İzmir Su ve Kanalizasyon İdarelerinin (sırası ile ASKİ, İSKİ, İZSU) elektrik tüketimleri 2010 GWh[2] ile tüm Türkiye'nin elektrik tüketiminin yaklaşık yüzde birini oluşturmuştur. Enerji maliyeti, su işlemleri arasında da oldukça büyük yer tutmaktadır[3]. Su ve atıksu hizmetlerinde işletme maliyetinin %5-%30'u elektrik harcamalarıdır[4]. Yüksek enerji maliyetleri, tesis işletmecilerini zorlamakta ve ülkedeki tüm vatandaşların hizmet almasına engel olmaktadır. TÜİK verilerine göre Türkiye nüfusunun %45'ine içme ve kullanma suyu arıtma tesisi hizmeti[5], %30'una atıksu arıtma tesisi hizmeti ulaşmamaktadır[6]. İçme ve kullanma suyu olarak çekilen suyun %43'ü[5], oluşan atıksuyun %14'ü[6] arıtılmamaktadır. Türkiye'de de şimdiden yoğun enerji talebi olan su işlemlerinin nüfus artışına paralel olarak su talebinin artması ile gelecekte daha çok enerjiye ihtiyaç duyacağı aşikârdır. Su işlemlerinde kullanılan enerjinin temiz-tükenmez enerji kaynaklarından elde edilmesiyle önemli ekonomik, çevresel ve sosyal kazanımlar sağladığı farklı teorik ve pratik çalışmalarla kanıtlanmıştır.

Temiz-tükenmez enerji kaynaklarının entegre edilebilmesi için öncelikle enerji yoğunluğu ve temiz-tükenmez enerji kaynak potansiyeli belirlenmelidir. Su işlemlerinin enerji yoğunluğunun yalnızca ülkeden ülkeye değil, aynı ülke içinde ve hatta aynı teknoloji kullanan tesisler arasında bile değiştiği düşünüldüğünde, Türkiye'de tüm su işlemlerinin tesis bazında enerji yoğunluğunun belirlenmesi önem arz etmektedir.

Bu çalışmayla, Türkiye'deki su ve atıksu arıtım işlemlerinin enerji tüketimi ve temiz-enerji kullanma kapasitesi konusunda mevcut durumunu literatüre ve karar vericilere veri tabanı niteliğinde sunarak su işlemlerinde tüketilen enerjinin bir kısmının ya da tamamının temiz-tükenmez enerji kaynakları kullanılarak karşılanmasının ekonomik ve çevresel analizinin gerçekleştirilmesi hedeflenmektedir.

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2. İletişim Bilgisi

1 - Ad Soyad: *

Adınız Soyadınız

2 - E-posta: *

ornek@ornek.com

3 - Kurumda Bağlı Olduğunuz Birim: *

3. Kurumsal Bilgi

4 - Tesis Adı: *

5 - İl: *

Lütfen Seçiniz

6 - İlçe: *

7 - Tesisinizdeki arıtma çeşitleri nedir?

- [ ] Ön (İlk) Arıtma
- [ ] Birincil (Fiziksel/Mekanik) Arıtma
- [ ] İkincil Arıtma (Biyolojik ve Kimyasal Arıtma /Karbon Giderimi)
- [ ] İleri Arıtma (Gelişmiş Arıtma /Azot ve Fosfor Giderimi)

8 - Lütfen, tesisinizde kullanılan süreçleri/ekipmanları işaretleyiniz.

- [ ] Terfi Merkez(ler)i
- [ ] Havalandırmalı Lagünler
- [ ] Ön (İlk) Arıtma: Kaba Izgaralar
- [ ] Ön (İlk) Arıtma: İnce Izgaralar
- [ ] Ön (İlk) Arıtma: Kum-Yağ Tutucular (Sıyırıcı ve atıcı dâhil)
- [ ] Birincil (Fiziksel/Mekanik) Arıtma: Ön Çöktürme (Çökeltme) Havuzları
- [ ] Birincil (Fiziksel/Mekanik) Arıtma: Çökelme Verimi için Kimyasal İlavesi (Otomatik)
- [ ] İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma: Havalandırma Havuzları
- [ ] İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma: Aktif Çamur (Biyolojik Azot, Karbon ve Fosfor Giderimi)
- [ ] İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma: Damlatmalı Filtre
- [ ] İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma: Döner Biyodisk
- [ ] İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma: Geri Devir Pompaları
- [ ] İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma: Pompalama
- [ ] İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma: Son Çöktürme (Çökeltme) Havuzları
- [ ] Dezenfeksiyon: Kızılötesi (UV) Işını
- [ ] Dezenfeksiyon: Isıl Arıtma
- [ ] Dezenfeksiyon: Membran Filtrasyonu

- [ ] Dezenfeksiyon: Klorlama
- [ ] Dezenfeksiyon: Ozonlama
- [ ] Dezenfeksiyon: Hidrojen Peroksit Uygulanması
- [ ] Deşarj Ünitesi
- [ ] Çamur İşlemleri: Çamur Pompaları
- [ ] Çamur İşlemleri: Bant Filtre/Belt Pres (Çamur Susuzlaştırma/Yoğunlaştırma/Çamur Keki)
- [ ] Çamur İşlemleri: Santrifüj Dekantörler (Çamur Susuzlaştırma/Yoğunlaştırma/Çamur Keki)
- [ ] Çamur İşlemleri: Tampon Tankı
- [ ] Çamur İşlemleri: Çamur Çürütme
- [ ] Çamur İşlemleri: Çamur Kurutma
- [ ] Çamur İşlemleri: Kojenerasyon Ünitesi (Kuru Gaz/Biyogaz Tankı)
- [ ] Koku Giderme
- [ ] Diğer Işlemler

4. Tesisin Mevcut Ve Gelecekteki Enerji Kullanımı, Enerji Kaynağı Dağılımı

9 - Lütfen, tesisinizle ilgili aşağıda sorulan bilgileri mümkün olduğunca doldurun. Lütfen yanıtları en yakın tam sayı olarak verin.

	Miktar
Hizmet Verilen Nüfus (Kişi)	
Tesis Tasarım Kapasitesi (metreküp/gün)	
Günlük Arıtılan Su (metreküp/gün)	
Çalışma Oranı (yıllık saat)	
Atık Çamur Miktarı (kg/gün)	
Ortalama tesis deşarjı (metreküp/gün)	
Şebekeden kullanılan toplam elektrik (birim belirtiniz: MWh/yıl ya da TL/yıl)	
Tesis tarafından üretilen enerji (MWh/yıl)	
Şebekeye verilen elektrik (MWh/yıl)	
Şebekeye verilen gaz (milyon metreküp/yıl)	
Varsa enerji satışından elde edilen toplam gelir (TL/yıl)	

10 - Tesisinizde yenilenebilir enerji üretimi yapıyorsanız kaynağını ve miktarını belirtiniz.

	Miktar (MWh/yıl)
Güneş Enerjisi (Fotovoltaik)	
Hidroelektrik	
Rüzgar Enerjisi	
Jeotermal	
Oksijensiz (Anaerobik) çürütme: Üretilen elektrik	
Oksijensiz (Anaerobik) çürütme: Toplanan ve kullanılan ısı	
Oksijensiz (Anaerobik) çürütme: Gaz/ısı kaybı	
Karışık çürüme (yemek atığı dâhil): Üretilen elektrik	
Karışık çürüme (yemek atığı dâhil): Toplanan ve kullanılan ısı	
Karışık çürüme (yemek atığı dâhil): Gaz/ısı kaybı	
Isı dönüşümü/Çamur yakma: Üretilen elektrik	
Isı dönüşümü/Çamur yakma: Toplanan ve kullanılan ısı	
Isı dönüşümü/Çamur yakma: Gaz/ısı kaybı	
Diğer Elektrik Üretim Teknolojileri	

11 - Lütfen, tesisinizde bulunan aşağıdaki ekipmanların sayısı, gücü ve çalışma saatini belirtiniz.

	Adet	Güç (kW)	Çalışma Saati (s/gün)
Blower			
Difüzör			
Santrifüj Dekantör			
Belt Press (Bant Filtre)			
Pompalar			
Geri Devir Pompaları			

12 - Lütfen, tesisinizde ham suyun girişinden çıkışına kadar geçtiği işlemlerde harcanan elektrik/enerji miktarını, birimini seçerek (MWh/yıl ya da TL/yıl kolonuna "x" koyarak) belirtiniz.

	MWh/yıl	TL/yıl	Toplamın yüzdesi (%)	Elektrik Tüketimi
Ön (İlk) Arıtma				
Ön (İlk) Arıtma: Kaba Izgaralar				
Ön (İlk) Arıtma: Terfi Merkez(ler)i				
Ön (İlk) Arıtma: İnce Izgaralar				
Ön (İlk) Arıtma: Kum-Yağ Tutucular (Sıyırıcı ve atıcı dâhil)				
Birincil (Fiziksel/Mekanik) Arıtma				
Birincil (Fiziksel/Mekanik) Arıtma: Ön Çöktürme (Çökeltme) Havuzları				
Birincil (Fiziksel/Mekanik) Arıtma: Çökelme Verimi için Kimyasal İlavesi (Otomatik)				
İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma				
İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma: Havalandırma				
İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma: Aktif Çamur (Biyolojik Azot, Karbon ve Fosfor Giderimi)				
İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma: Damlatmalı Filtre				
İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma: Döner Biyodisk				
İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma: Geri Devir Pompaları				
İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma: Pompalama				
İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma: Son Çöktürme (Çökeltme) Havuzları				
Dezenfeksiyon				
Deşarj Ünitesi				
Çamur İşlemleri				
Çamur İşlemleri: Çamur Pompaları				
Çamur İşlemleri: Çamur Susuzlaştırma				
Çamur İşlemleri: Çamur Yoğunlaştırma				
Çamur İşlemleri: Çamur Çürütme				
Çamur İşlemleri: Çamur Kurutma				
Çamur İşlemleri: Kojenerasyon Ünitesi (Kuru Gaz/Biyogaz Tankı)				

13 - Tesisinizde ham suyun girişinden çıkışına kadar geçtiği işlemlerden en çok elektrik/enerji harcayan ilk üç işlemi seçiniz.

	1	2	3
Ön (İlk) Arıtma	☐	☐	☐
Ön (İlk) Arıtma: Kaba Izgaralar	☐	☐	☐
Ön (İlk) Arıtma: Terfi Merkez(ler)i	☐	☐	☐
Ön (İlk) Arıtma: İnce Izgaralar	☐	☐	☐
Ön (İlk) Arıtma: Kum-Yağ Tutucular (Sıyırıcı ve atıcı dâhil)	☐	☐	☐
Birincil (Fiziksel/Mekanik) Arıtma	☐	☐	☐
Birincil (Fiziksel/Mekanik) Arıtma: Ön Çöktürme (Çökeltme) Havuzları	☐	☐	☐
Birincil (Fiziksel/Mekanik) Arıtma: Çökelme Verimi için Kimyasal İlavesi (Otomatik)	☐	☐	☐
İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma	☐	☐	☐
İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma: Havalandırma	☐	☐	☐
İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma: Aktif Çamur (Biyolojik Azot, Karbon ve Fosfor Giderimi)	☐	☐	☐
İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma: Damlatmalı Filtre	☐	☐	☐
İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma: Döner Biyodisk	☐	☐	☐
İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma: Geri Devir Pompaları	☐	☐	☐
İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma: Pompalama	☐	☐	☐
İkincil Arıtma (Biyolojik ve Kimyasal Arıtma/Karbon Giderimi) & İleri (Gelişmiş) Arıtma: Son Çöktürme (Çökeltme) Havuzları	☐	☐	☐
Dezenfeksiyon	☐	☐	☐
Deşarj Ünitesi	☐	☐	☐
Çamur İşlemleri	☐	☐	☐
Çamur İşlemleri: Çamur Pompaları	☐	☐	☐
Çamur İşlemleri: Çamur Susuzlaştırma	☐	☐	☐
Çamur İşlemleri: Çamur Yoğunlaştırma	☐	☐	☐
Çamur İşlemleri: Çamur Çürütme	☐	☐	☐
Çamur İşlemleri: Çamur Kurutma	☐	☐	☐
Çamur İşlemleri: Kojenerasyon Ünitesi (Kuru Gaz/Biyogaz Tankı)	☐	☐	☐

5. Yenilenebilir Enerji Kaynakları (YEK) Konusundaki Değerlendirmeniz

14 - Türkiye'de YEKDEM yönetmeliğinin atıksu arıtma tesislerinde YEK kullanımını desteklediğine ne kadar katılıyorsunuz?

	0	1	2	3	4	5	
Fikrim Yok	○	○	○	○	○	○	Kesinlikle Katılıyorum

15 - Atıksu arıtma tesislerine YEK entegre edilmesinin önündeki engelleri ve riskleri seçiniz:

- ☐ Yenilenebilir enerji kaynak kapasitesinin eksikliği engeli
- ☐ Finansal engeller
- ☐ Teknik bilgi eksikliği engeli
- ☐ Enerji arz güvenliği riski
- ☐ Gelişmiş teknoloji eksikliği engeli
- ☐ Diğer

16 - Tesisinize YEK entegre etmenizi, aşağıdaki etmenlerden hangileri ne kadar motive eder? (1: Hiç motive etmez; 3: Ne motive eder, ne motive etmez; 5: Çok motive eder)

	1	2	3	4	5
Tesis için en düşük maliyetli (TL/kWh) enerji kaynağını elde etmek	☐	☐	☐	☐	☐
Arıtılan atıksuyun birim maliyetini azaltmak	☐	☐	☐	☐	☐
Tesisin stratejik enerji yönetimi planı	☐	☐	☐	☐	☐
Belediyenin (ya da diğer yerel yönetimin) stratejik planı	☐	☐	☐	☐	☐
Toplumsal beklentileri karşılayarak sosyal sorumluluk göstermek	☐	☐	☐	☐	☐
Güvenilirliği ve güç kalitesini sağlamak için gerilim ve frekans yönetimini geliştirmek	☐	☐	☐	☐	☐
Tesisin enerji güvenliğini artırmak ve şebeke değişkenliğini azaltmak	☐	☐	☐	☐	☐
Şebekenin genel performans ve dayanıklılığına katkı sağlamak	☐	☐	☐	☐	☐
Koku, gürültü gibi diğer tesis dışı etkiler de dâhil çevresel yönetimi iyileştirmek	☐	☐	☐	☐	☐
Türkiye'nin sera gazı salımını azaltmasına destek vermek	☐	☐	☐	☐	☐
Yasal olarak yükümlü olmak	☐	☐	☐	☐	☐

Yukarıdakiler dışında etmenler varsa:

17 - Yararlanacak tesisler için, öncelik sırasına göre, şu anda önemli olan ve önümüzdeki 10 yıl içinde önemli olacağını düşündüğünüz üç enerji türünü sıralayınız.

	Günümüzde 1.	Günümüzde 2.	Günümüzde 3.	10 yılda 1.	10 yılda 2.	10 yılda 3.
Alg Biyoyakıt	☐	☐	☐	☐	☐	☐
Oksijensiz (Anaeorobic Digestion) Çürüme	☐	☐	☐	☐	☐	☐
Yakıt hücresi	☐	☐	☐	☐	☐	☐
Jeotermal Enerji	☐	☐	☐	☐	☐	☐
Isı geri kazanımı	☐	☐	☐	☐	☐	☐
Hidroelektrik	☐	☐	☐	☐	☐	☐
Güneş Enerjisi (Fotovoltaik)	☐	☐	☐	☐	☐	☐
Isıl Dönüşüm (Ör: çamur yakma)	☐	☐	☐	☐	☐	☐
Rüzgâr Enerjisi	☐	☐	☐	☐	☐	☐

18 - Lütfen aşağıdaki soruları tesisinizin YEK kullanımına göre yanıtlayınız.

	Evet	Hayır
Elektrik depolama var mı? (Elektrik depolama için şebekeye bağlı alet/sistem)	☐	☐
Gelecekte elektrik depolamayı arttırma planınız var mı?	☐	☐
Tesisinizin elektrik tüketimini azaltmaya yönelik uygulanan işlemler var mı?	☐	☐

Elektrik depolamayı arttırma planınız varsa, yüzde kaç? (%)

ör: 40

Sayıyı doğrudan yazabilirsiniz.

Tesisinizin elektrik tüketimini azaltmaya yönelik uyguladığınız işlemler varsa tanımlayınız:

6. Son Sözler (Tercihen)

19 - Konuya ve ankete ilişkin düşünce ve yorumlarınızı öğrenmekten memnuniyet duyarız:

Kaydet

Appendix B. Ethical Approval

T.C.
HACETTEPE ÜNİVERSİTESİ
Rektörlük

2 2 Ocak 2018

Sayı : 35853172/ 433-309

FEN BİLİMLERİ ENSTİTÜSÜ MÜDÜRLÜĞÜNE

İlgi: 05.01.2018 tarih ve 27 sayılı yazınız.

Enstitünüz Temiz Tükenmez Enerji Anabilim Dalı tezli yüksek lisans programı öğrencilerinden **Gözde ODABAŞ'ın Doç. Dr. Merih AYDINLAP KÖKSAL** danışmanlığında yürüttüğü **"Su İşlemlerinde Temiz- Tükenmez Enerji Kaynakları Kullanımının Ekonomik ve Çevresel Analizi"** başlıklı tez çalışması, Üniversitemiz Senatosu Etik Komisyonunun **16 Ocak 2018** tarihinde yapmış olduğu toplantıda incelenmiş olup, etik açıdan uygun bulunmuştur.

Bilgilerinizi ve gereğini rica ederim.

Prof. Dr. Rahime M. NOHUTCU
Rektör a.
Rektör Yardımcısı

Hacettepe Üniversitesi Rektörlük 06100 Sıhhiye-Ankara
Telefon: 0 (312) 305 3001 - 3002 • Faks: 0 (312) 311 9992
E-posta: yazimd@hacettepe.edu.tr • www.hacettepe.edu.tr

Ayrıntılı Bilgi için:
Yazı İşleri Müdürlüğü
0 (312) 305 1008

Gözde H. bilgi verdim

Appendix C. Formal Letter from Hacettepe University for Survey

Tarih: 17.05.2018 16:12
Sayı: 23154132-300-E.00000051575

E.00000051575

T.C.
HACETTEPE ÜNİVERSİTESİ
Fen Bilimleri Enstitüsü Müdürlüğü

Sayı : 23154132-300
Konu : Anket Talebi (Gözde Odabaş)

.... SU VE KANALİZASYON İDARESİ GENEL MÜDÜRLÜĞÜ

Enstitümüz Temiz Tükenmez Enerjiler Anabilim Dalı Yüksek Lisans programı N14323259 Numaralı öğrencisi Gözde Odabaş'ın ***"Su işlemlerinde Temiz-Tükenmez Enerji Kaynakları Kullanımının Ekonomik ve Çevresel Analizi"*** isimli tez çalışmasında kullanılmak üzere anket çalışması online olarak hazırlanmış ve Üniversitemiz Etik Kurul Komisyonundan ilgili izin alınmıştır. Ekte yer alan anket talep yazısında belirtilen şekilde Genel Müdürlüğünüz işletimindeki her bir İçme ve Kullanma Suyu Arıtma Tesisi ve Atık su Arıtma Tesisi Özelinde bu anketlerin doldurulması hususunda yardımlarınızı saygılarımla rica ederim.

e-imzalıdır
Prof. Dr. Menemşe GÜMÜŞDERELİOĞLU
Enstitü Müdürü

Ek: - H.Ü. Etik Komisyon Onayı
- Anket Talep Yazısı

Evrakın elektronik imzalı suretine https://belgedogrulama.hacettepe.edu.tr adresinden 354cc07d-202e-4d49-9a60-4d78ad851056 kodu ile erişebilirsiniz.
Bu belge 5070 sayılı Elektronik İmza Kanunu'na uygun olarak Güvenli Elektronik İmza ile imzalanmıştır.

Hacettepe Üniversitesi Fen Bilimleri Enstitüsü Müdürlüğü 06800 Beytepe-ANKARA
Telefon:(0 312) 297 68 65 Faks:(0 312) 299 21 57 E-posta:fenbilmaster@hacettepe.edu.tr İnternet Adresi: www.fenbilimleri.hacettepe.edu.tr

Tarih: 17.05.2018 16:12
Sayı: 23154132-300-E.00000051575

E.00000051575

Dağıtım:
Ankara Su ve Kanalizasyon İşleri Genel Müdürlüğü
Adana Su ve Kanalizasyon İdaresi Genel Müdürlüğü
Antalya Su ve Atıksu İdaresi Genel Müdürlüğü
Bursa Su ve Kanalizasyon İdaresi Genel Müdürlüğü
Diyarbakır Su ve Kanalizasyon İdaresi Genel Müdürlüğü
Gaziantep Su ve Kanalizasyon İdaresi Genel Müdürlüğü
İstanbul Su ve Kanalizasyon İdaresi Genel Müdürlüğü
İzmir Su ve Kanalizasyon İdaresi Genel Müdürlüğü
Kocaeli Su ve Kanalizasyon İdaresi Genel Müdürlüğü
Konya Su ve Kanalizasyon İdaresi Genel Müdürlüğü
Mersin Su ve Kanalizasyon İdaresi Genel Müdürlüğü
Şanlıurfa Su ve Kanalizasyon İdaresi Genel Müdürlüğü (Şuski)

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Telefon:(0 312) 297 68 65 Faks:(0 312) 299 21 57 E-posta:fenbilmaster@hacettepe.edu.tr İnternet Adresi:
www.fenbilimleri.hacettepe.edu.tr

Appendix D. Survey Request Letter from the Thesis Supervisor

EK 2 – Anket Talep Yazısı

03/05/2018

DAĞITIM YERLERİNE

Sayın İlgili,

Hacettepe Üniversitesi Temiz Tükenmez Enerjiler Anabilim Dalı bünyesinde, yüksek lisans öğrencisi Gözde Odabaş'ın, danışmanlığımda gerçekleştirdiği tez çalışması kapsamında su ve atıksu işlemlerinde tüketilen enerjinin ortaya konularak azaltılması için tesislerde kullanılabilecek temiz-tükenmez enerji kaynaklarının belirlenmesi ile ilgili anketler hazırlanmıştır.

Bu anketler ile, su ve atıksu tesislerinin mevcut enerji kaynakları, toplam ve proses bazlı enerji kullanımı ve gelecekteki potansiyel enerji kaynağı dağılımı üzerine temel veri ve görüşlerin toplanarak literatürden elde edilen verilerle karşılaştırmada kullanılması hedeflenmiştir.

Anketler için Hacettepe Üniversitesi Etik Komisyonundan gerekli izin alınmıştır. Ankete katılım tamamen gönüllülük esasına dayalıdır. Anket, genel olarak kişisel rahatsızlık verecek sorular içermemektedir. Ancak, anket formunu doldururken herhangi bir nedenden ötürü kendinizi rahatsız hissederseniz cevaplama işini yarıda bırakabilir; anket formunu doldurduktan sonra yanıtlarınızın kullanılması konusunda fikrinizi değiştirirseniz anket yanıtlarınızın imha edilmesi için tez danışmanı Doç. Dr. Merih Aydınalp Köksal'a ve/veya Gözde Odabaş'a başvurabilirsiniz. Anketin uygulanması için onay vermeden önce veya anket sırasında, çalışma hakkında merak ettiğiniz herhangi bir konuda tez öğrencisi Gözde Odabaş'a ulaşabilirsiniz.

İçme ve Kullanma Suyu Arıtma Tesisleri ve Atıksu Arıtma Tesislerine yönelik **online olarak hazırlanan** bu iki ankete aşağıdaki bağlantılardan ulaşabilirsiniz:

- İçme ve Kullanma Suyu Arıtma Tesisleri: **https://www.jotform.com/gozdeodabas/icme-suyu-aritma-enerji-tuketimi**
- Atıksu Arıtma Tesisleri: **https://www.jotform.com/gozdeodabas/atiksu-aritma-enerji-tuketimi**

Genel Müdürlüğünüz işletimindeki her bir İçme ve Kullanma Suyu Arıtma Tesisi ve Atıksu Arıtma Tesisi özelinde bu anketlerin doldurulması hususunda desteğinizi rica ederim.

Saygılarımla,

Merih

Doç. Dr. Merih Aydınalp Köksal
Hacettepe Üniversitesi, Çevre Mühendisliği Bölümü
Beytepe Kampüsü, Beytepe, 06800, Ankara

Bilgi için:

Gözde ODABAŞ	Doç. Dr. Merih AYDINALP KÖKSAL
E-posta: gozdeodbs@gmail.com	**E-posta:** aydinalp@hacettepe.edu.tr
Tel: +90 554 813 16 03	**Ofis Tel:** +90 312 297 78 00 (dâhili: 123)

Appendix E. Thesis Originality Report

HACETTEPE UNIVERSITY
GRADUATE SCHOOL OF SCIENCE AND ENGINEERING
THESIS/~~DISSERTATION~~ ORIGINALITY REPORT

HACETTEPE UNIVERSITY
GRADUATE SCHOOL OF SCIENCE AND ENGINEERING
TO THE DEPARTMENT OF CLEAN RENEWABLE ENERGIES

Date: 04/10/2019

Thesis Title / Topic: Investigation of Economic and Environmental Impacts of the Use of Solar and Biogas Resources in Urban Wastewater Treatment Plants

According to the originality report obtained ~~by myself~~/my thesis advisor by using the *Turnitin* plagiarism detection software and by applying the filtering options stated below on 03/10/2019 for the total of 96 pages including the a) Title Page, b) Introduction, c) Main Chapters, d) Conclusion sections of my thesis entitled as above, the similarity index of my thesis is 6%.

Filtering options applied:

1. Bibliography/Works Cited excluded
2. Quotes excluded / ~~included~~
3. Match size up to 5 words excluded

I declare that I have carefully read Hacettepe University Graduate School of Science and Engineering Guidelines for Obtaining and Using Thesis Originality Reports; that according to the maximum similarity index values specified in the Guidelines, my thesis does not include any form of plagiarism; that in any future detection of possible infringement of the regulations I accept all legal responsibility; and that all the information I have provided is correct to the best of my knowledge.

I respectfully submit this for approval.

04.10.2019

Date and Signature

Name Surname:	Gözde Odabaş
Student No:	N14323259
Department:	Clean Renewable Energies
Program:	M.Sc.
Status:	☒ Masters ☐ Ph.D. ☐ Integrated Ph.D.

ADVISOR APPROVAL

APPROVED.

Assoc. Prof. Dr. Merih Aydınalp KÖKSAL

Appendix F. Curriculum Vitae

1. **Name:** Gözde ODABAŞ
2. **Contact:** gozde.odabas@hacettepe.edu.tr
3. **Date of Birth:** 07/04/1991
4. **Nationality:** T.C.
5. **Civil Status:** Single
6. **Education:**

Institution	Degree or Diploma obtained
Hacettepe University, Institute of Science; Ankara, TR, 2015 - 09/2019	M.Sc. in Renewable Energies
Bilkent University, Faculty of Engineering; Ankara, TR, 2008 – 2014 (Full Scholarship)	B.Sc. in Industrial Engineering

7. **Language Skills:** (1: Low; 5: Excellent)

Language	Reading	Speaking	Writing
Turkish (native)	5	5	5
English	5	5	5
Spanish	3	2	2

8. **Membership of Professional Bodies:** Executive Board Member at the Research Association of Rural Environment and Forestry (RAREF) and Resource, Environment and Climate Change Association
9. **Other Skills:** Excellent knowledge of MS Office programs (Word, PowerPoint, Excel, Access). Moderate knowledge of PhotoShop, WordPress, CSS, HTML, Java. Basic knowledge of QGIS, Arena, GAMS, SQL, HOMER Software. Fast-learner on web/computer technologies
10. **Current Position:** Expert
11. **Years Within Firm:** ~5 years
12. **Key Qualifications:**

- ✓ +5 years of experience in **survey preparation, research, un/structured data collection, integrating data across multiple data sources, applying statistical and evaluation measures to complex data, scientific reporting including data visualization**
- ✓ Familiarity with **Java, CSS, VBA, SQL languages**
- ✓ 5 years of experience in **project development, management and implementation** in a multinational organization
- ✓ Proven **analytical abilities** and **writing skills**
- ✓ Experience in technical assistance field in terms of **understanding** the **needs of clients and the beneficiaries** as well as the important actors in the field
- ✓ Proven **consultancy experience in EU environment and climate change sectors** for national environmental administrations and agencies
- ✓ Understands the **UN, EU, CEE, and national governance and administrative systems**

13. **Specific Eastern Countries Experience:**

Country, Date	Country, Date
Turkey, 2014 – current	India, June 2013 – September 2013

14. **Professional Experience Record:**

Date	11/2015 – Current (Past: 08/2014 – 09/2015)	Location	Ankara, Turkey

<table>
<tr><td>Company</td><td>Regional Environmental Center (REC) Turkey</td><td>Position</td><td>Expert (Past: Consultant)</td></tr>
<tr><td colspan="4">✓ <u>Technical Assistance for Developed Analytical Basis for Formulating Strategies and Actions Towards Low Carbon Development (06/2017-06/2020):</u> 10 technical presentations on the EU Emission Trading System Directive (ETSD) Regulatory Impact Assessment (RIA). Two technical presentations on Effort Sharing Decision RIA. 3 Online surveys on ETSD, Fuel Quality Directive (FQD) and Carbon Capture and Storage Directive (CCSD) and 3 evaluation reports of the results. Two technical presentations on building sector. Two drafts and two final RIA Reports on ETSD and ESD. A draft and a final SIA Report on the building sector.
✓ <u>Waste Management in Turkey “Experiences on Dual Sorting and Current Situation on Public Awareness Activities” (11/2018-03/2019):</u> An Online survey targeting selected municipalities. Five study visits and workshops. A Study Visit Report. A Current Situation on Dual Sorting Report including analysis of the survey results.
✓ <u>GreenPack on the Road (09/2018-09/2019):</u> Taking part in the concept design team and poster/infographic design team for the Recycling Exhibition (https://yesilkutu.org/sergi/sergiicerik/). An online registration form for the visitor school groups. Coordinator and supervisor of the exhibition guides.
✓ <u>Preparation of GHG Inventory and Climate Action Plan for Denizli Metropolitan Municipality (03/2018-12/2018):</u> An Online Knowledge Test on Climate Change. An Online Personal Carbon Footprint Calculator. A City GHG Inventory Report and Local Climate Action Plan. A Current Situation Report. A Stakeholder Map and Report. Technical presentations at trainings for students and personnel of municipality.
✓ <u>Preparation of GHG Inventory and Climate Action Plan for Kocaeli Metropolitan Municipality (12/2017-08/2018:</u> A City GHG Inventory Report and Local Climate Action Plan. 3 study visits. A Study Visit Report and a presentation.
✓ <u>Turkish Business Leaders’ Response to Climate Change Project (08/2016 – 01/2017):</u> An Online Survey on Climate Change targeting CEOs of leader enterprises in Turkey. A public event for survey results dissemination. A Report on Survey Results.
✓ <u>Strengthening Institutional Capacity in Environmental Management in Turkey (ÇEKAP) Project (ESEI Project) (08/2014 – 10/2016):</u> 5 online stakeholder surveys. 3 regional workshops for mayors. 7 working group meetings. +5 consultation meetings. 1 national conference on sustainable cities. A draft and a final RIA Report on EU Packaging Waste Directive. A Legal Gap Analysis and Report. An online survey for “problems faced by municipalities” and a survey results report. A National Strategy Document for Local Environmental Action Plan (LEAP). Two Implementation Guidelines for Municipalities on Packaging and Packaging Waste and Waste Accumulators and Batteries Directives.</td></tr>
<tr><td>Date</td><td>01/2014 – 10/2014</td><td>Location</td><td>Bursa, Turkey</td></tr>
<tr><td>Company</td><td>Savcan Textile</td><td>Position</td><td>Project Researcher</td></tr>
<tr><td colspan="4">Supporting project's senior consultant by;
✓ Benchmark analysis of possible markets, current situation, similar and possible business models
✓ Data compiling, analyzing and visualizing
✓ Preparing presentations
✓ Organising meetings within the project team & keeping meeting minutes</td></tr>
<tr><td>Date</td><td>06/2013 – 09/2013</td><td>Location</td><td>Jaipur, India</td></tr>
<tr><td>Company</td><td>Aura Thai, Spa & Saloon</td><td>Position</td><td>Operations & Sales Intern</td></tr>
<tr><td colspan="4">✓ Social Media Page Manager
✓ Cashier
✓ Welcoming & informing guests about services
✓ Arranging schedules of staff</td></tr>
<tr><td>Date</td><td>09/2013 – 01/2014
09/2012 – 12/2012
01/2011 – 06/2011</td><td>Location</td><td>Ankara, Turkey</td></tr>
<tr><td>Company</td><td>Bilkent University</td><td>Position</td><td>Teaching Assistant</td></tr>
<tr><td colspan="4">Laboratory Assistants of two Courses named:</td></tr>
</table>

- Introduction to Computing and Programming for Social Sciences
- Introduction to Programming for Engineering and Science Students

✓ Assisting students in weekly projects of Excel & MATLAB & Java during the laboratory hours
✓ Evaluating the projects of students

15. Others: (Publications/Books/Articles; Conferences)

Publications

✓ Sayman, R. U., Akpulat, O., Baş, D., Odabaş, G., GHG Inventory Report of Kocaeli Metropolitan Municipality, Regional Environmental Center (REC) Turkey, Ankara, Turkey, September 2018 link (in TR)
✓ Sayman R. U. and Odabaş G., The Role of the Cities in the Fight Against the Climate Change, Turkish Healthy Cities Association, 2018, link (in TR)
✓ Sayman, R. U., Baş, D., Odabaş, G., Akpulat, O., Turkish Business Leaders' Response to Climate Change: CEO Survey Research Report, Regional Environmental Center (REC) Turkey, Ankara, Turkey, December 2016 link (in TR)
✓ Sayman, R. U., Akpulat, O., Packaging, and Packaging Waste Directive Implementation Guideline for Municipalities, Regional Environmental Center (REC) Turkey, Ankara, Turkey, 2016 (Contributor) link (in TR)
✓ Sayman R. U., Akpulat O., Şakı M. Ö., Waste Batteries Directive Implementation Guideline for Municipalities, Regional Environmental Center (REC) Turkey, Ankara, Turkey, 2016 (Contributor) link (in TR)

Additional projects and outputs

✓ Economic and Environmental Analysis of Renewable Energy Usage in Wastewater Processes in Turkey (Master Thesis under the academic advisory of Assoc. Prof. Dr. Merih Aydınalp Köksal) (06/2018-09/2019)– Hacettepe University, Renewable Energies Department: *An Online survey targeting WWTPs managements. A database of WWTPs in metropolitan municipalities including data such as energy consumption/production, biogas production, treated wastewater, etc. Simulation of WWTP systems via HOMER Software to assess the economic and environmental impact of biogas and photovoltaic system integration to the system.*
✓ Updating the Situation of Remnant Forests in the Inner Anatolia and Establishing Conservation Proposals (11/2016-06/2018) - RAREF: -Voluntary Work- *Socio-economic field studies (focus group surveys via interviews). Interview Results Analysis and Reporting. Hosting at the workshop.*

Selection of Events/Trainings Attended as Trainee/Speaker

✓ Trainee: Co-Benefits of Renewable Energy for Turkey (09/2019) – Sustainable Power System Planning for Turkey
✓ Speaker: Bursagaz Conference on Sustainable Life (11/2018)
✓ Trainee: ISES 2018 (08/2018) – International Summer School on Energy
✓ Trainee: Awarenergy (06/2018) – Summer School on Energy Giacomo Ciamician

- ✓ Trainee: IMPRESSIONS Summer School (05/2018) – Exploring Climate Change Challenges and Solutions in the Real World: from Research to Practice
- ✓ Trainee: RAREF (10/2017): Forests Ecosystem Training
- ✓ Trainee: Venice International University – VIU (06/2017): Critical Infrastructure Resilience Training
- ✓ Trainee: RAREF (06/2017): Dendrology Training & Steps Ecosystem Training
- ✓ Trainee: Bilkent University (06/2011): Operations Analysis and Design Project Winner
- ✓ Trainee: ODS Eğitim (04/2011): Certificate of Social Media Training

Certificates, Awards, and Scholarships

- ✓ TOEFL iBT Score (24/03/2018) – 98 (Reading: 27 / Listening: 24 / Speaking: 24 / Writing: 23)
- ✓ Bilkent University (06/2014 & 06/2011 & 06/2010): Honour awarded by Faculty of Engineering
- ✓ Bilkent University (09/2008 – 06/2014): Full scholarship
- ✓ College Admission (ÖSS-08/2008): Placed 949th among 1.5 million applicants nationwide, Turkey