A Thesis
entitled
Estimation of Renewable Energy for a Wastewater Treatment Plant
by
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Submitted to the Graduate Faculty as partial fulfillment of the requirements for the
Master of Science Degree in Electrical Engineering

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The purpose of this study is to estimate renewable energy (RE) that can be generated for a wastewater treatment plant (WWTP) using its internal and external RE sources. A typical large-scale WWTP has two important internal RE sources – namely, digester gas (methane) and biosolids. Digester gas is generated during the process of digesting wastewater. After the digestion process, the leftover sediment in the digester is referred to as “silt” or “biosolids”. Biosolids have sufficient heat content that can be recovered as energy by incineration. Therefore, biosolids are considered the second internal source of RE. Additionally, there are external sources of RE for the use in the WWTPs, such as solar, wind, and landfill. This study estimates the energy that could be generated from these RE sources using different energy models for the City of Toledo WWTP, Toledo, Ohio. The data for the year 2008 are used in the analysis.

One mega watt (MW) solar photovoltaic plant is considered to estimate solar energy. Wind energy is estimated for a turbine diameter of 40 m with different heights (100 m, 150 m, and 300 m). The solar insolation and wind velocity are obtained from the NASA Climatic Center for the City of Toledo. Landfill energy is estimated using the LANDGEM model for the Hoffman Road Landfill. Wastewater flow rate (Q) is used to
estimate a) digester energy, b) biosolids energy, and c) plant energy consumption for the City of Toledo WWTP. The average wastewater flow rate of the City of Toledo WWTP is 77.44 million gallons per day.

Uncertainty and sensitivity analyses are conducted for individual RE sources and total energy. Uncertainty is computed as a measure of goodness of a model and evaluated by introducing 5%, 10%, and 20% error in the total mean energy of the energy models. The Wind energy model shows the highest uncertainty (95%) when compared to solar (85%), landfill (75%), and internal RE (84%) sources. The uncertainty of total energy is reduced to 50% for combined case of external RE sources with internal RE sources for the total energy estimation. Sensitivity of the total energy is evaluated between parameters of the energy models in terms of rank correlation (RC) coefficient and contribution to variance (CV). Wastewater flow rate shows the highest RC coefficient and CV, when compared with wind velocity, solar insolation, and methane generation rate for total energy estimation. This analysis supports the use of RE for sustainable WWTP operations.

Internal energy is proportional to wastewater flow rate, and not all the WWTPs in the United States have the capacity to process large quantities of wastewater, and sometimes they do not have a supportive environment for the external energy sources. Therefore, harvesting internal and external energy sources of the plant is uncommon for all WWTPs. For the City of Toledo WWTP, internal energy sources generate most of the energy (80%) required for the plant operation, but the combination of internal and external energy sources produces more energy than the plant energy consumption. The additional energy can be fed back to the grid to offset the energy bill of the WWTP.
I am dedicating this thesis to the people of Veerappalli Village, beloved family members
and wife Sudhamoorthy.
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<th>Description</th>
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<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>AEO</td>
<td>Annual Energy Output</td>
</tr>
<tr>
<td>BEF</td>
<td>Bio Energy Factor</td>
</tr>
<tr>
<td>BOD</td>
<td>Biochemical Oxygen Demand</td>
</tr>
<tr>
<td>bCOD</td>
<td>biodegradable Chemical Oxygen Demand</td>
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<tr>
<td>Btu</td>
<td>British thermal unit</td>
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<tr>
<td>CHP</td>
<td>Combined Heat and Power</td>
</tr>
<tr>
<td>COD</td>
<td>Chemical Oxygen Demand</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DEO</td>
<td>Daily Energy Output</td>
</tr>
<tr>
<td>ER&lt;sub&gt;anaerobic&lt;/sub&gt;</td>
<td>Energy Recovered from anaerobic process</td>
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<tr>
<td>ER&lt;sub&gt;incineration&lt;/sub&gt;</td>
<td>Energy Recovered from incineration of biosolids</td>
</tr>
<tr>
<td>kWh</td>
<td>kilo watt hour – unit of energy</td>
</tr>
<tr>
<td>kW</td>
<td>kilo watt – unit of power</td>
</tr>
<tr>
<td>mgd</td>
<td>Million gallons per day</td>
</tr>
<tr>
<td>MFC</td>
<td>Microbial Fuel Cell</td>
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<tr>
<td>MW</td>
<td>Mega watt – unit of power</td>
</tr>
<tr>
<td>PCU</td>
<td>Power Control Unit</td>
</tr>
<tr>
<td>PV</td>
<td>Photo Voltaic</td>
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<tr>
<td>RE</td>
<td>Renewable Energy</td>
</tr>
<tr>
<td>RO</td>
<td>Reverse Osmosis</td>
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<tr>
<td>WWTP</td>
<td>Wastewater Treatment Plant</td>
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</table>
Chapter 1

Introduction

The term “green technology” can be defined as a commercial product or a system created not only for economic motive but also for environmental, social, and cultural benefits [1]. Basically, its context depends upon application and technology. Different applications, such as transportation versus living spaces or military versus civilian, have varying needs of renewable energy sources. One significant application for renewable energy could be in the recycling of waste material. Specifically, one such area of interest could be wastewater treatment plants (WWTP). Green technology can make such plants less harmful to the environment. An added benefit would be conservation of valuable fossil fuels that are in limited supply. Green technology emphasizes recycling, minimizing environmental impact and supporting sustainable development.

There are numerous parameters to describe a technology, whether it is green technology or not. The following are parameters that describe green technology in wastewater treatment applications:

a) Treatment performance in relation to effluent standard

b) Robustness of process
c) Emissions of various pollutants into the environment
d) Waste or sludge production
e) Recycling or reuse potential
f) Energy consumption, including source of energy used
g) Use of chemicals
h) Use of area
i) Environmental nuisance
j) Environmental benefits

The above parameters can be varied for different applications and systems. This study considers only energy consumption of wastewater treatment plants instead of all parameters. The objective of the study is to demonstrate the viability of renewable energy sources for wastewater treatment plants.

1.1 Purpose of the study

The survival of all civilization depends on the availability of fresh water. To imagine the future development of society without water is not within our thinking capability. Water plays a substantial role in our lives, so the saving and cleaning of water resources are essential duties for all. Modern industrialization and modern urbanization started between World War I and World War II. These two wars resulted in unparalleled technological advancement. As the technology started to expand, the growth of industrialization was uninterrupted. Eventually, industrialization led to pollution, which affects the quality of water, air, and soil.

The negative environmental impact of industrialization has affected the quality of water, soil, and air and created consequences that impact world economics and quality of life.
These impacts have included hurricanes, earthquakes, forest fires, tsunamis and other disasters. Environmental impact creates huge losses to society in terms of life, money, and shelter. Once people around the world realized the negative impact of industrialization on the environment, they started to protect the prime resources of the environment through various environmental protection agencies.

Environmental impacts motivated researchers to develop various technologies to protect and clean the prime resources of the earth. One such example is wastewater treatment technology that removes contamination in the water produced by human activities. The probability of spreading diseases through water decreases when the quality of water increases. This is essential to survival and sustaining harmony with nature because most diseases are caused by the poor quality of water. If the water is less contaminated, then air and soil are also less contaminated. Therefore, treating the water helps to protect other prime resources of the earth and the well being of all.

1.2 Specific Motivation as it Relates to Wastewater Treatment Plants

The objective of wastewater treatment plants is to reduce environmental impact by removing the toxic agents that are found in the wastewater. Wastewater is produced by human and animal daily activities. Wastewater treatment is an essential part of the modern industrial world [2]. If we do not treat wastewater with an optimal effort, then it is difficult to live in a healthy society. Therefore, investing in and optimizing wastewater treatment plants are important in order to create a sustainable living environment where threats to human life and the environment are greatly reduced.

Are wastewater treatment plants really helping to reduce the negative impact on the environment? Are wastewater treatment plants sustainable to the environment? The
answer is neither yes nor no. Most of the wastewater treatment plants were built based on fossil fuel energy, which is non-renewable in nature. Wastewater treatment plants produce enormous amounts of greenhouse gases while digesting wastewater molecules through various chemical processes. Energy consumption and greenhouse gas emissions depend upon wastewater treatment plant capacity. The capacity of a wastewater treatment plant is defined by population and industrial activities.

For example, the City of Toledo built a wastewater treatment plant in 1922 that has an average treatment capacity of 77.44 million gallons of water per day and serves approximately 398,000 people [3]. It consumes 4.5 MW of base power and 9.5 MW of peak power from fossil fuel. It produces digester gases (13.7 MMBtu/hr-Million British thermal units per cubic foot per hour) which include CH₄, CO₂, and NOₓ, and others.

The United States of America has approximately 16,583 wastewater treatment plants [4], and each such plant consumes fossil fuel-based energy and produces large amounts of greenhouse gases. Consumption of fossil fuel-based energy and production of greenhouse gases depend upon wastewater treatment plant (WWTP) capacity. The number of large-scale wastewater treatment plants [4] located in the US is shown in Figure 1-1. Therefore, the primary focus of this study is to reduce energy consumption of wastewater treatment plants using existing renewable energy technology to make the plants more sustainable to the environment and society.
Figure 1-1: Location of large scale wastewater treatment plants in the USA [4]
Chapter 2

Literature Review

Brix (1999) described the following types of water treatments [1]. These are a) aquaculture b) wetland, and c) conventional wastewater treatment plants. He provided an optimal definition of green technology and discussed the “life cycle approach” to evaluate greener systems that are implemented at water treatment facilities. He discussed the key concepts for evaluating green water treatment plants. These concepts are sustainability, energy consumption, use of less non-renewable energy, and environmental impacts.

Arias and Brown (2009) analyzed the evaluation of cost in terms of energy, construction, efficiency, operation, and maintenance of a constructed wetland treatment system (CWTS) in comparison with a water stabilization pond (WSP), and sequencing batch reactor (SBR) at Bogotá Savannah, Colombia [29]. They concluded that a constructed wetland treatment system is cost effective in terms of energy when compared to a WSP and sequencing batch reactor.

Min et al. (2005) conducted a pilot study on fuel cells for a wastewater treatment plant [30]. Wastewater (swine water) consists of organic and inorganic matter that can be used to produce electricity using fuel cells. One such example of fuel cells is a microbial fuel
cell (MFC). It can generate electricity from marine sediments, anaerobically digested sludge, food wastewater, and domestic wastewater. The power density depends on the type of reactor and the specific source of the organic matter.

Min et al. (2005) compared power generation capabilities using a single-chamber microbial fuel cell and a double-chamber microbial fuel cell. The microbial fuel cell performance was tested in three different test conditions.

The test conditions were the following:

a) Pre-treated wastewater

b) Highly concentrated wastewater

c) Diluted wastewater.

Each test condition had a different power density value. The microbial fuel cell is a viable solution to treat wastewater (swine water) and generate electricity, but it needs additional research efforts to scale up and optimize the treatment processes.

Antoniadis et al. (2007) explained the combined wastewater treatment system for remote locations where a conventional wastewater treatment system is not economically possible for a small community [2]. He combined photo catalytic and constructed wetland systems for wastewater treatment, and the treated water was used to irrigate local land. Compared to conventional systems of wastewater treatment, the main advantages of the combined systems include the following:

a) Low cost of establishment and operation,

b) Ability to treat wastewater with great variability of hydraulic and pollutants load,

c) No need for an additional disinfection method
d) Utilization of solar energy and natural processes

e) Opportunity of reuse wastewater

Bjorklund et al. (2001) have discussed a wastewater treatment plant in Sweden [31]. Bjorklund explained the utilization of local and global resources for the wastewater treatment plant and also provided a percentage of resources utilized for each process of the wastewater treatment plant. Here, all resources were measured in terms of an emergy indicator. The emergy indicator was a measurement of the amount of direct and indirect energy of one kind that was used to generate a resource. He concluded that the electricity produced using the digestion of sewage sludge is inefficient because it takes twice the amount of resources compared to electricity produced in Sweden.

Carta et al. (2003) discussed wind energy harvesting for reverse-osmosis-based desalination plants [11]. He conducted a real-time field study of the application of wind energy to power eight reverse-osmosis (RO) plants and a plant control subsystem located in the Canary Islands. These reverse-osmosis plants acted as a load to wind energy, and they were operated by two strategies. The first one was a base strategy (first connect, last disconnect) in which the first reverse-osmosis plant was connected to wind energy and the last one was disconnected from wind energy. The second strategy was described as a ring strategy in which the order of connection and disconnection was the same for each plant. These automatic processes were controlled by programmable logic controllers and onsite digital computers.

Carta et al. (2003) supported the conclusion that the wind energy prototype was a successful autonomous demonstration of water desalination in the islands. This prototype
can be applied to any seashore area where potable water is paramount to coastal populations.

Du et al. (2007) explained various geometric designs of microbial fuel cells that were used in wastewater treatment and bio energy applications [32]. The microbial fuel cell acted as a bio reactor that converts chemical energy in the chemical bonds of organic compounds to electrical energy through catalytic reactions of microorganisms under anaerobic conditions.

Du et al. (2007) concluded that the microbial fuel cell is a promising technology for wastewater treatment and bio energy harvesting for wireless sensor networks at remote locations on a small scale. In energy harvesting, every technology faces difficulty in scaling up, as does the microbial fuel cell.

Martinez et al. (2009) analyzed the importance of life-cycle assessment in various stages of the wind turbine process from cradle to grave [10]. The life-cycle assessment included a) how much energy is invested, b) the environmental impact, and c) the payback period to produce one kilo watt hour of energy from a wind turbine. He followed international standard organization (ISO14040) management protocols and used a SimaPro software tool for quasi process information to calculate the life-cycle assessment.

Martinez et al. (2009) justified the wind energy technology. It has a positive environmental benefit rather than a negative impact on the environment, but he recommended improving the efficiency of wind turbines and their component manufacturing processes.

Nouri et al. (2006) conducted research on energy recovery from a wastewater treatment plant in Iran [6]. The focal point of research was on the methane production potential of
domestic wastewater. The operating costs of wastewater treatment plants have increased substantially due to the increase in energy cost.

One of the solutions to reduce energy costs of wastewater treatment plant is to use available energy in the digester gas. It is an essential renewable energy produced from the process of anaerobic digestion of raw sludge. The efficiency of the anaerobic process depends on the following parameters:

a) The solid content of the sludge

b) The biodegradability of the organic material

c) The retention time

d) The digester temperature

Nouri et al. (2006) showed the calculations of energy content, electricity potential, and capable electricity production capability for combined heat and power systems from estimated methane production.

A typical wastewater treatment plant uses only 26% of its total methane production from the plant. The remaining 74% of produced methane is burned in flare and wasted. If the plant managers intend to optimize the electrical energy in various units and processes of the plant and convert methane into electrical and heat energy using combined heat and power generation (CHP) technology, then most of the plants energy, up to 97%, can be recovered from the plant itself. These calculations can be applied to develop a renewable energy management tool for wastewater treatment plants.

Raman et al. (2006) developed a tool to assess waste management system within hospitals [7]. Hospital waste consists of toxic and non toxic waste. The toxic waste has to be handled carefully to avoid spreading disease in the hospital environment. Sometimes
workers do not have awareness or knowledge about different types of toxic waste products, which are sometimes mixed with regular waste. Therefore, separating the toxic waste from other waste is an important job in the hospitals. This kind of assessment tool is used to create awareness and increase the knowledge of workers in hospitals. Also, this tool is used to maintain proper waste management records for monthly and annual inspections. This approach can be applied to develop a renewable energy management tool for wastewater treatment plants.

Developing a renewable energy management tool for wastewater treatment plants is essential to monitor day-by-day energy consumption of the plant. Here, the tool should be able to calculate energy production from the wastewater treatment plant based on the following energy sources: solar, wind, digester gas, landfill gas, and incineration of biosolids. Also, this tool will support the assessment of the life-cycle analysis of wastewater treatment plants.

Coffey (2008) investigated the potential use of renewable energy sources, such as solar and wind, for wastewater treatment plants [12]. A suitable application in which renewable energy has found favor in wastewater treatment sectors around the world is to provide power for membrane ultrafiltration and reverse-osmosis (RO) desalination. These two processes are energy intensive and very important for producing potable water for both developed and developing worlds.

Using only renewable energy is difficult in the complete operations of wastewater treatment plants. It can be combined with biogas-based combined heat and power generation systems for sustainable plant operations.
Ackermann and Soder (2000) reviewed how wind energy technology has evolved since it was initially used for large-scale power generation [13]. These researchers specified various applications of wind energy technology, such as sea water desalination, water pumping, etc. Wind energy can be applied to wastewater treatment plants where optimal wind speed is possible. In particular, if the wastewater treatment plants are located nearer to the seashore, then they are suitable for wind-based power generation.

Prabhakant and Tiwari (2009) calculated a) cost, b) carbon credits, and c) return on investment of standalone photo voltaic systems in India [17]. The economic life of standalone photo voltaic systems was considered at 30, 40, and 50 years for calculations. Conventional power generation systems require long-distance (>500km) transmission and distribution networks to reach the end consumer. In addition, they experience power loss during transmission, and they increase the cost of power generation. Standalone photo voltaic systems have the advantage of onsite power generation and minimum loss. They requires small-distance (<1km) transmission and distribution networks. These calculations can be applied to any locations where the average solar insolation is greater than 150 Watt/m² and photo voltaic panel efficiency is 8% to 10%.

Based on Prabhakant and Tiwari’s (2009) calculations, solar photo voltaic systems can be applied on small and large scales for a given area of land. The rooftops and some areas within the wastewater treatment plants can be used for solar photo voltaic power generation. But solar photo voltaic based power generation cannot help in the continuous mode of operations of the plant. These issues can be resolved by accommodating other sources of power generation. One such example is utilization of digester gas for power generation in wastewater treatment plants.
Bloomquist (2002) reviewed different methods, cost, and efficiency of combined heat and power generation technology for various energy markets [26]. For example, micro turbine-based combined heat and power generation can be used for schools, hospitals, and individual houses. A second example is that gas turbine-based combined heat and power generation can be used for large-scale utilities, industries, and wastewater treatment facilities. The combined heat and power generation provides onsite power and heat with 70% to 80% efficiency. It is the best technology to use at larger facilities, such as wastewater treatment plants, because wastewater treatment facilities need onsite electrical and thermal energy for continuous operation.

Robert (1978) calculated the total energy consumption for municipal wastewater treatment plants [28]. He addressed three major issues related to energy calculations. These are a) energy consumption for the total plant, b) energy consumption for plant operation, and c) recoverable energy from the plant. These energy calculations were based on plant wastewater treatment capacity. The plant capacities were 1mgd (millions of gallons treated per day), 10 mgd, and 100 mgd.

Robert (1978) proposed a generic relationship between energy consumption and wastewater treatment capacity for three types of plants. The plant types were as follows:

a) Primary plants

b) High-rate trickling filter plants and

c) Activated sludge plants
Approximate total electrical power consumption was expressed for each plant type as follows:

a) kWh /mg = 390 mgd \(^{-0.15}\) for primary plants

b) kWh /mg = 700 mgd \(^{-0.12}\) for high rate trickling filter plants and

c) kWh /mg = 1100 mgd \(^{-0.06}\) for high activated sludge plants

Robert did not consider solar, wind, and landfill gas as appropriate energy sources for municipal wastewater treatment plants. In those days, the cost of renewable energy sources was high compared to fossil fuel-based energy sources. Therefore, choosing the most appropriate renewable energy source and its implementation in wastewater treatment plants is very important for sustainable plant operation. Also, renewable energy will help to mitigate the energy crises of the next century.

Stillwell et al. (2010) calculated the optimal recoverable energy from the wastewater treatment plants in the US [21]. He used two renewable energy resources from the plants. One is bio gas from the anaerobic process and the second is biosolids. Biosolids are
produced by digestion of wastewater sludge. These two sources can be used for electricity generation by utilization of biogas and incineration of bio solids.

Based on Stillwell et al.’s (2010) calculations, the energy consumption of wastewater treatment plants can be reduced by 2.6% to 27% if it uses bio gas and biosolids for electricity generation. The remaining 70% of the energy is based on fossil fuel. One can possibly choose renewable energy for wastewater treatment plants to help reduce future energy demand, cut cost, and create a sustainable environment.

Since the production of biogas and biosolids depends upon the quantity of wastewater, then small-scale wastewater treatment facilities may experience problems related to energy recovery. The reason is that small-scale facilities (< 5mgd) do not have sufficient quantities of wastewater to produce bio gas and bio solids. Solar and wind-based energy is suitable for small-scale treatment facilities to offset energy costs.

Kordes (1985) proposed a computer simulation model to calculate energy demand and energy production of wastewater treatment plants [33]. The model consists of subroutines that represent the various treatment processes of the plants. However, all these subroutines require input data from the plant. These are measured at periodic intervals and then calibrated. Kordes did not specify the reliability of the model or the applications of the computer model to different types of treatment plants.

This observation clearly indicates that we need an assessment tool to calculate energy demand and energy production for different types of wastewater treatment plants. The assessment tool should have an option to accommodate renewable energy for wastewater treatment plants.
Chapter 3

Objective and Problem Statement

Wastewater treatment plants in the United States consume approximately 4% of the total energy produced per year in the United States [5]. Thus, wastewater treatment applications consume a significant fraction of the energy production of the nation. This energy consumption has seasonal variations. These variations occur because of differing demands for water use according to weather conditions that change with the seasons. Most of the plant operation budget (approximately 80%) has been spent on electricity that is used for water processing and distribution [5]. However, the WWTP has the capacity to recover its own energy from various sources [6].

The major energy recovery sources of WWTP are as follows:

a) Solar
b) Wind
c) Landfill gas
d) Digester gas
e) Biosolids

These energy sources are referred to as renewable energy sources. They do not have a negative impact on environment and society. These sources can improve the
sustainability of wastewater treatment plants and benefit the next generation. Thus, the objectives are to estimate total renewable energy of the WWTP plant, calculate the energy consumption of the WWTP plant, and study the uncertainty and degree of sensitivity involved in the parameters of renewable energy sources \[7\].

Table 3.1 shows the parameters chosen for the renewable energy (RE) sources of the WWTP plant for this study.

Table 3.1: Parameter Selection for the Renewable Energy Sources of the WWTP

<table>
<thead>
<tr>
<th>No</th>
<th>Renewable energy Source</th>
<th>Parameter</th>
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<tbody>
<tr>
<td>1</td>
<td>Solar</td>
<td>Solar Insolation</td>
</tr>
<tr>
<td>2</td>
<td>Wind</td>
<td>Wind Velocity</td>
</tr>
<tr>
<td>3</td>
<td>Landfill</td>
<td>Solid Waste</td>
</tr>
<tr>
<td>4</td>
<td>Digester</td>
<td>Wastewater Flow Rate</td>
</tr>
<tr>
<td>5</td>
<td>Biosolids</td>
<td>Wastewater Flow Rate</td>
</tr>
</tbody>
</table>

If excess energy is produced, it will be fed into the local utility grid to offset the energy cost of the wastewater treatment plant. In case the recovered energy is less than the plant energy consumption, then the balance of energy will be taken from the local utility grid. The concept is shown in Figure 3-1 as individual system blocks.

Figure 3-1: Block Diagram of a Renewable Energy Management System
The generic modeling of energy consumption of a wastewater treatment plant is an intricate process. The reason is that each plant requires a different treatment process based on population and treatment capacity [5].

To start with, we can consider the following cases:

a) Energy recovery is less than or equal to the energy requirement of the plant, and

b) Energy recovery is greater than the energy requirement of the plant. Then the excess energy will be fed into the local utility grid to offset the energy cost of the wastewater treatment plant.

One could avoid storing electrical energy using battery banks at the plant location since storing electrical energy increases plant operation cost.
Chapter 4

Renewable Energy for Wastewater Treatment Plants

4.1 Available RE Sources for WWTP

Renewable energy (RE) can be defined as an energy source which can be produced and replenished naturally without having a negative impact on the environment. Several conventional RE sources include sunlight, wind, tides, rain, and geothermal. At appropriate locations, sunlight and wind are major sources of RE. Additionally, for wastewater treatment plants, there are two other RE sources. These are digester gas and biosolids, which are byproducts of water purification. Moreover, landfill gas can be used in wastewater treatment plants as a renewable source of energy. If sunlight and wind are adequately available, then they can be applied in wastewater treatment plants. We need to calculate energy from each of the above mentioned sources to make an estimation of the amount of balance energy produced over that obtained from the grid.
4.2 Wind Energy

Wind energy can be harvested by using wind turbines. Wind turbines can be divided into two types. The first type is a large-scale, 3MW wind turbine, which is used to yield wind energy of more than 10 m/s. The second type is a small-scale wind turbine, having a capacity of less than 500kW and producing wind energy at lower speeds of 10 m/s. Therefore, choosing wind energy as a potential renewable source for a WWTP depends heavily on the speed of the wind available for that location. Toledo has 5-6 m/s (meter per second) of average wind speed at 80 m height. Thus, Toledo falls into the second category and requires low-capacity wind turbines. The wind resource map of Toledo at 50 m and 80 m is shown in the Figures 4-2 and 4-3 [8].

Figure 4-1: Aerial View of the Bay area WWTP at the City of Toledo [9]

Figure 4-3 shows the wind energy potential for Toledo at 80 m height, and this can easily be harvested using small-scale wind turbines. As seen in Figure 4-1, the huge open space at the bay area treatment plant provides an opportunity to produce wind energy on a large
scale using more than one wind turbine. One large wind turbine is not suitable for Toledo due to less than average wind speed availability.

The Toledo Bay Area wastewater treatment plant requires a base load of 4.5 MW and peak load of 9.5 MW [9]. This large-scale energy can be harvested using multiple small-scale wind turbines. The plant load value was obtained from a report produced by Middough Inc, [9].

Figure 4-2: Wind speed map of Ohio State at the height of 50 m [8]
Wind is not a constant source of energy. It varies according to the height, location, ambient temperature, and atmospheric stability. For this reason, a typical WWTP requires an additional power control unit to regulate the power obtained from the ever-changing wind energy. Such a system is shown in Figure 4-4. The average efficiency of the power control unit (PCU) is 95.2%. The PCU efficiency calculation is shown in Appendix A.
The excess energy produced by a wind turbine can be fed back to the local utility grid. The cost of energy produced by wind is comparable to the energy produced by a conventional grid supply. This cost can be further reduced by employing large-scale wind harvesting methods but the water treatment plant being discussed requires a fewer number of wind turbines to meet its energy requirement.

Atlantic County in New Jersey installed 5 wind turbines to power its wastewater treatment plant. Each turbine has a 1.5 MW capacity and produces 7.5 MW of power [11,12]. Most of the power goes to the reverse osmosis desalination and filtration process. The Atlantic County wastewater treatment plant is shown in Figure 4-5.
4.2.1 Generic Wind Energy Model

Wind turbines are 20% to 40% efficient at converting wind into energy, and their theoretical efficiency is 59%. The following generic model is used to calculate the power produced from a wind turbine [13], and its unit is measured in kilowatts. The detailed derivation of the wind power model is shown in Appendix C.

\[
\text{Power} = \frac{1}{2} \rho_a C_p A V^3
\]  

(4.1)

where, power is measured in watt, \( C_p \) = betz coefficient for maximum power, \( 16/27=0.59 \). \( \rho_a \) = air density (kg/m\(^3\)), \( A \) = rotor swept area (m\(^2\)), \( V \) = wind speed (meter per second). From the above model, one can conclude that the power depends on wind speed and rotor swept area. The power produced from a wind turbine increases when the rotor has a larger swept area.
4.2.2 Wind Energy Model for Small Wind Turbine

A small wind turbine can be classified by looking at the rotor diameter, which varies from 4m to 40m. The energy produced from wind turbines varies according to the rotor diameter and available wind resource. The annual energy output produced from small wind turbines is estimated by the following equation [14, 42], and detailed derivation of the annual energy output is shown in Appendix C.

\[ AEO = 1.6005 \frac{D^2 V^3}{gLk_0} \]  

(4.2)

where, AEO = annual energy output (kWh per year), D= rotor diameter (meter), V=annual average wind speed (meter per second).

To calculate the wind energy for wastewater treatment plant applications, the rotor diameter is varied from 4 m to 40 m for annual average wind speed measured at 50 m, 100 m, 150 m, and 300 m. The wind speed data was taken from the NASA Climate Center [15]. The following Table shows the annual average wind speed data measured in Toledo. The place is represented in terms of latitude and longitude. Latitude and longitude of the city of Toledo is 41.66 and -83.55.

<table>
<thead>
<tr>
<th>Lat 41.66</th>
<th>Lon -83.5</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>June</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Annual Average Wind Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50m</td>
<td></td>
<td>6.7</td>
<td>6.31</td>
<td>6.57</td>
<td>6.40</td>
<td>5.61</td>
<td>5.12</td>
<td>4.58</td>
<td>4.40</td>
<td>4.73</td>
<td>5.43</td>
<td>6.09</td>
<td>6.33</td>
<td>5.68</td>
</tr>
<tr>
<td>100m</td>
<td></td>
<td>7.43</td>
<td>7.00</td>
<td>7.28</td>
<td>7.10</td>
<td>6.22</td>
<td>5.68</td>
<td>5.08</td>
<td>4.88</td>
<td>5.24</td>
<td>6.02</td>
<td>6.75</td>
<td>7.02</td>
<td>6.31</td>
</tr>
<tr>
<td>150m</td>
<td></td>
<td>7.9</td>
<td>7.44</td>
<td>7.74</td>
<td>7.54</td>
<td>6.61</td>
<td>6.03</td>
<td>5.40</td>
<td>5.18</td>
<td>5.57</td>
<td>6.40</td>
<td>7.18</td>
<td>7.46</td>
<td>6.70</td>
</tr>
<tr>
<td>300m</td>
<td></td>
<td>8.76</td>
<td>8.25</td>
<td>8.59</td>
<td>8.37</td>
<td>7.33</td>
<td>6.69</td>
<td>5.99</td>
<td>5.75</td>
<td>6.18</td>
<td>7.10</td>
<td>7.96</td>
<td>8.28</td>
<td>7.44</td>
</tr>
</tbody>
</table>

Table 4.1: Average wind speed of the City of Toledo at 50 m, 100 m, 150 m, 300 m
4.3 Solar Photo Voltaic

Solar photo voltaic is a well proven technology to convert the sun’s energy into electricity. Many wastewater treatment plants have an uncovered rooftop area and land areas that can be used for solar photo voltaic panel installations to harvest the optimal energy required for it. To harvest solar energy using PV panels, we need an average radiation of 4-6 kWh/m²/day. This is possible at the Toledo bay area WWTP. Figure 4-6 gives solar radiation information [16] from 1961-1990 for Toledo, and it gives assurance that we can use solar PV panels for the Toledo bay area WWTP to produce renewable energy.

![Variability of Latitude Fixed-Tilt Radiation](image)

Figure 4-6: Average monthly solar radiation of the City of Toledo from year 1961 to 1990

The Figure 4-7 shows the Morristown wastewater treatment facility in New Jersey, which has a 578 kW capacity of solar PV in rooftop, car port, and ground mounted arrays. They provide 40% of the electricity that is necessary to operate the plant and produce 635,800
kilowatt hours per year. This has averted a discharge of 359 metric tons of CO$_2$ into the atmosphere or burning (combusting) equivalent fossil fuel. The approximate amount of CO$_2$ produced per kWh of energy generation is 0.544 gram.

![Figure 4-7: Installed Solar PV on the roof of Morrison WWTP-New Jersey](image)

Most of the plants are operated by conventional electric grid supply and need an additional PCU to consume power from solar PV. The PCU [17] converts direct voltage DC into alternating voltage-AC. The efficiency of the power control unit is 95.02% percent and is shown in Figure 4-8.
4.3.1 Generic Solar Photo Voltaic Energy Model

Solar photovoltaic modules are 8% to 12% efficient at converting solar radiation into electrical energy. The photovoltaic panel efficiency depends on the type of material, ground conditions, and panel operating temperatures. The following generic model is used to calculate the energy produced from the solar photovoltaic module [17], and their unit is measured in kilowatt hours per day.

\[
\text{Solar energy} = \eta I_w A h
\]  

(4.3)

where, \(\eta\) = solar photovoltaic panel efficiency, \(I_w\) = average solar insolation of the place \((W/m^2)\), \(A\) = area of the solar photovoltaic panel \((m^2)\), \(h\) = number of sun shine hours per day. The solar photovoltaic energy is DC, and it must be converted into AC by using a power control unit, which is nothing but an inverter. The net energy produced after conversion is shown in the following equation 4.4.

\[
\text{Net Energy} = (\text{Solar energy}) \eta_{in}
\]  

(4.4)

where, Energy = energy produced from the solar photovoltaic panel \((kWh/day)\), \(\eta_{in}\) = efficiency of the inverter. The number of solar panels required to meet the plant energy can be modeled by the following equation 4.5.
\[ N_{\text{panel}} = \frac{E_T}{E_{\text{Panel}}} \] (4.5)

Total energy of the wastewater treatment plant cannot be produced by solar PV technology. They need a big investment and land area, and also they are not economical for wastewater treatment plants. However, a certain portion of the plant energy can be harvested by solar PV technology. The following Table 4.2 shows the monthly average solar insolation and energy of the City of Toledo for year 2008.

Table 4.2: Average of solar insolation and energy for the City of Toledo

<table>
<thead>
<tr>
<th>Toledo</th>
<th>Month</th>
<th>Solar Insolation (kWh/m²/day)</th>
<th>Net Energy (10³ kWh per day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>1.83</td>
<td>3.94</td>
<td></td>
</tr>
<tr>
<td>Feb</td>
<td>2.05</td>
<td>4.42</td>
<td></td>
</tr>
<tr>
<td>Mar</td>
<td>3.02</td>
<td>6.51</td>
<td></td>
</tr>
<tr>
<td>Apr</td>
<td>5.36</td>
<td>11.56</td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>5.83</td>
<td>12.58</td>
<td></td>
</tr>
<tr>
<td>Jun</td>
<td>5.57</td>
<td>12.02</td>
<td></td>
</tr>
<tr>
<td>Jul</td>
<td>6.60</td>
<td>14.24</td>
<td></td>
</tr>
<tr>
<td>Aug</td>
<td>5.76</td>
<td>12.43</td>
<td></td>
</tr>
<tr>
<td>Sep</td>
<td>4.54</td>
<td>9.80</td>
<td></td>
</tr>
<tr>
<td>Oct</td>
<td>3.26</td>
<td>7.03</td>
<td></td>
</tr>
<tr>
<td>Nov</td>
<td>1.80</td>
<td>3.89</td>
<td></td>
</tr>
<tr>
<td>Dec</td>
<td>1.40</td>
<td>3.02</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>3.94</td>
<td>8.45</td>
<td></td>
</tr>
</tbody>
</table>

4.4 Landfill Gas

Landfills are basically storage locations of municipal solid wastes. If landfills are not operated properly, then they pose one of the biggest threats to the environment, as they can produce greenhouse gases in large amounts. Wastewater treatment plants are the major producers of solid wastes. Sometimes these solid wastes are used for landfill to produce landfill gas. Methane makes up the largest percentage of greenhouse gases [19]. Methane is a powerful greenhouse gas and is harmful to the environment, but it can be
used to generate power and heat using cogeneration technology (Combined Heat and Power Generation).

### 4.4.1 Landfill Gas Estimation Model – LANDGEM

The amount of methane gas produced from a landfill can be modeled by the following equation 4.6 [19]. This Model is based on the first order decomposition rate equation proposed by the US Environmental Protection Agency ():

$$ Q_{CH4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} k L_0 \frac{M_i}{10} e^{-kt_{ij}} $$  \hspace{1cm} (4.6)

where, $Q_{CH4} = $ Annual methane generation in the year of calculation (m$^3$/year)

i = 1- year time increment

n = Year of calculation – initial year of waste acceptance

j = 0.1 – year time increment

k = Methane generation rate, 0.05 per year

$L_0$ = Potential methane generation capacity, 170 (m$^3$/Mg)

$M_i$ = Mass of waste accepted in the $i^{th}$ year (Mg)

$t_{ij}$ = Age of the $j^{th}$ section of waste mass $M_i$ accepted in the $i^{th}$ year (decimal years, e.g., 3.2 years)

The landfill and methane gas generation estimations are based on the LANDGEM tool and are shown in Table 4.3. Landfill gas consists of methane, CO$_2$, and other non-methane organic components (NMOC). Here, Hoffman Road landfill data is used for the estimation of landfill gas. The LANDGEM tool is able to calculate and provide results up to the year 2115, but it considers default data after 2009. We have real data for the waste
acceptance rate up to 2009 from the Ohio EPA. Appendix E explains the derivation of the LANDGEM model. Table 4.3 shows the landfill gas generation up to the year 2009.

Table 4.3: Hoffman road landfill, methane generation rate

<table>
<thead>
<tr>
<th>No</th>
<th>Year</th>
<th>Waste Acceptance Rate-M$_i$ Tons/year</th>
<th>Landfill Gas Generation (ft$^3$/min)</th>
<th>Methane gas Generation (ft$^3$/min)</th>
<th>CO$_2$ Generation (ft$^3$/min)</th>
<th>NMOC Generation (ft$^3$/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 to 11</td>
<td>1975 To 1985</td>
<td>0</td>
<td>0.000E+00</td>
<td>0.000E+00</td>
<td>0.000E+00</td>
<td>0.000E+00</td>
</tr>
<tr>
<td>12</td>
<td>1986</td>
<td>174,000</td>
<td>0.000E+00</td>
<td>8.834E+01</td>
<td>8.834E+01</td>
<td>7.067E-01</td>
</tr>
<tr>
<td>13</td>
<td>1987</td>
<td>0</td>
<td>1.767E+02</td>
<td>8.403E+01</td>
<td>8.403E+01</td>
<td>6.722E-01</td>
</tr>
<tr>
<td>14</td>
<td>1988</td>
<td>99,059</td>
<td>1.681E+02</td>
<td>8.302E+02</td>
<td>8.302E+02</td>
<td>1.042E+00</td>
</tr>
<tr>
<td>15</td>
<td>1989</td>
<td>211,005</td>
<td>2.604E+02</td>
<td>2.310E+02</td>
<td>2.310E+02</td>
<td>1.848E+00</td>
</tr>
<tr>
<td>16</td>
<td>1990</td>
<td>219,850</td>
<td>4.620E+02</td>
<td>3.314E+02</td>
<td>3.314E+02</td>
<td>2.651E+00</td>
</tr>
<tr>
<td>17</td>
<td>1991</td>
<td>199,617</td>
<td>6.627E+02</td>
<td>4.165E+02</td>
<td>4.165E+02</td>
<td>3.332E+00</td>
</tr>
<tr>
<td>18</td>
<td>1992</td>
<td>187,993</td>
<td>8.331E+02</td>
<td>4.917E+02</td>
<td>4.917E+02</td>
<td>3.933E+00</td>
</tr>
<tr>
<td>19</td>
<td>1993</td>
<td>177,046</td>
<td>9.833E+02</td>
<td>5.576E+02</td>
<td>5.576E+02</td>
<td>4.461E+00</td>
</tr>
<tr>
<td>20</td>
<td>1994</td>
<td>172,584</td>
<td>1.115E+03</td>
<td>6.180E+02</td>
<td>6.180E+02</td>
<td>4.944E+00</td>
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<tr>
<td>21</td>
<td>1995</td>
<td>184,536</td>
<td>1.236E+03</td>
<td>6.815E+02</td>
<td>6.815E+02</td>
<td>5.452E+00</td>
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<tr>
<td>22</td>
<td>1996</td>
<td>186,610</td>
<td>1.363E+03</td>
<td>7.430E+02</td>
<td>7.430E+02</td>
<td>5.944E+00</td>
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<tr>
<td>23</td>
<td>1997</td>
<td>199,886</td>
<td>1.486E+03</td>
<td>8.083E+02</td>
<td>8.083E+02</td>
<td>6.466E+00</td>
</tr>
<tr>
<td>24</td>
<td>1998</td>
<td>200,689</td>
<td>1.617E+03</td>
<td>8.708E+02</td>
<td>8.708E+02</td>
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<tr>
<td>25</td>
<td>1999</td>
<td>197,782</td>
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<td>9.287E+02</td>
<td>9.287E+02</td>
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<td>26</td>
<td>2000</td>
<td>195,713</td>
<td>1.857E+03</td>
<td>9.828E+02</td>
<td>9.828E+02</td>
<td>7.862E+00</td>
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<td>27</td>
<td>2001</td>
<td>189,904</td>
<td>1.966E+03</td>
<td>1.031E+03</td>
<td>1.031E+03</td>
<td>8.250E+00</td>
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<tr>
<td>28</td>
<td>2002</td>
<td>187,967</td>
<td>2.063E+03</td>
<td>1.076E+03</td>
<td>1.076E+03</td>
<td>8.611E+00</td>
</tr>
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<td>29</td>
<td>2003</td>
<td>179,560</td>
<td>2.153E+03</td>
<td>1.115E+03</td>
<td>1.115E+03</td>
<td>8.920E+00</td>
</tr>
<tr>
<td>30</td>
<td>2004</td>
<td>190,280</td>
<td>2.230E+03</td>
<td>1.157E+03</td>
<td>1.157E+03</td>
<td>9.258E+00</td>
</tr>
<tr>
<td>31</td>
<td>2005</td>
<td>186,108</td>
<td>2.315E+03</td>
<td>1.195E+03</td>
<td>1.195E+03</td>
<td>9.563E+00</td>
</tr>
<tr>
<td>32</td>
<td>2006</td>
<td>186,280</td>
<td>2.391E+03</td>
<td>1.232E+03</td>
<td>1.232E+03</td>
<td>9.853E+00</td>
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<tr>
<td>33</td>
<td>2007</td>
<td>158,547</td>
<td>2.463E+03</td>
<td>1.275E+03</td>
<td>1.275E+03</td>
<td>1.002E+01</td>
</tr>
<tr>
<td>34</td>
<td>2008</td>
<td>153,513</td>
<td>2.504E+03</td>
<td>1.325E+03</td>
<td>1.325E+03</td>
<td>1.015E+01</td>
</tr>
<tr>
<td>35</td>
<td>2009</td>
<td>140,795</td>
<td>2.538E+03</td>
<td>1.369E+03</td>
<td>1.369E+03</td>
<td>1.015E+01</td>
</tr>
</tbody>
</table>

(Note: E+03 = 10$^{+03}$)
From the Table 4.3, we can see that the methane generation potential is 50% of the total landfill gas. The overall heat content of landfill gas is 490 Btu per ft³ [20]. The average heat energy produced per hour from landfill gas for the year 2009 was (490) (60) (1269) = 37,308,600, or 33.31 million Btu per hour.

4.5 Digester Gas

Digester gas is produced using the anaerobic digester in wastewater treatment plants. The raw sludge from the treatment process is fed into the heated digester, where in the absence of air (oxygen), bacteria develop under slightly alkaline conditions and reduce the polluting solid matter to simple organic fatty acids, methane, carbon dioxide, and traces of other gases. Methane has the highest amount in percentage of gas generated, which accounts for about 65% of the total. Methane can be used for onsite power generation using cogeneration technology (Combined Heat and Power Generation).

4.5.1 Energy Recovered from Methane - Anaerobic Digestion Model 1

The quantity of methane generation depends upon plant waste handling capacity, and it can be calculated by the following equation [6]. The derivation of Eq. (4.7) is shown in Appendix D.

\[
V_{CH4} = 0.35 \left[ Q (S_0 - S) \left( \frac{10^3 g}{kg} \right) \frac{1}{1 + K_d SRT} \right]^{-1} \left( 1 - \frac{1.42 Y}{1 + K_d SRT} \right)
\]

(4.7)

where, \( V_{CH4} \) = volume of methane produced at standard condition (m³/day), 0.35 = theoretical conversion factor for the amount of methane produced from primary sludge (m³/day), \( Q \) = wastewater flow rate (m³/day), \( S_0 \) = biodegradable chemical oxygen demand in influent (mg/liter), \( S \) = biodegradable chemical oxygen demand in effluent (mg/liter), \( Y \) = yield coefficient (typical anaerobic reaction values range from 0.05 to
Typical methane content of biogas is 65%, and its typical energy content is 50.1 kilo Jules per gram. The conversion factor of kilo Jules to Watt hours is \( \frac{1}{3.6} \). Table 4.4 shows the methane generation rate of the City of Toledo WWTP estimated using equation 4.7 for the year 2008. It also shows the average wastewater flow rate (Q) and net electricity generation for year 2008.

### Table 4.4: Energy recovered from methane - anaerobic digestion model 1

<table>
<thead>
<tr>
<th>Year 2008</th>
<th>Q mgd</th>
<th>( V_{CH4} ) m(^3)/day</th>
<th>Net Electrical Energy ( 10^4 ) kWh per day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>82.43</td>
<td>1.352E+04</td>
<td>3.941</td>
</tr>
<tr>
<td>Feb</td>
<td>109.53</td>
<td>1.797E+04</td>
<td>5.236</td>
</tr>
<tr>
<td>Mar</td>
<td>127.66</td>
<td>2.094E+04</td>
<td>6.103</td>
</tr>
<tr>
<td>Apr</td>
<td>103.90</td>
<td>1.704E+04</td>
<td>4.967</td>
</tr>
<tr>
<td>May</td>
<td>64.10</td>
<td>1.052E+04</td>
<td>3.064</td>
</tr>
<tr>
<td>Jun</td>
<td>66.82</td>
<td>1.096E+04</td>
<td>3.194</td>
</tr>
<tr>
<td>Jul</td>
<td>85.84</td>
<td>1.408E+04</td>
<td>4.103</td>
</tr>
<tr>
<td>Aug</td>
<td>46.36</td>
<td>7.605E+03</td>
<td>2.216</td>
</tr>
<tr>
<td>Sep</td>
<td>57.12</td>
<td>9.370E+03</td>
<td>2.703</td>
</tr>
<tr>
<td>Oct</td>
<td>44.44</td>
<td>7.290E+03</td>
<td>2.124</td>
</tr>
<tr>
<td>Nov</td>
<td>54.53</td>
<td>8.945E+03</td>
<td>2.607</td>
</tr>
<tr>
<td>Dec</td>
<td>86.50</td>
<td>1.419E+04</td>
<td>4.135</td>
</tr>
<tr>
<td>Average</td>
<td>77.44</td>
<td>1.270E+04</td>
<td>3.702</td>
</tr>
</tbody>
</table>

(Note: E+03 = \( 10^{+03} \))

#### 4.5.2 Energy Recovered from Methane - Anaerobic Digestion Model 2

The quantity of energy recovered from methane through anaerobic digestion can be estimated by the following simple model, which is proposed by Stillwell et al. (2010) [21].
where, \( \text{ER}_{\text{anaerobic}} \) = energy recovery from anaerobic digestion (kWh/day) 
\( Q \) = wastewater flow rate (mgd), \( \text{BEF} \) = biogas energy factor (kWh/million gallon).

Reported biogas energy factors range from 350 to 525 kWh/million gallon for treated wastewater flows greater than 5 mgd. Table 4.5 shows the estimated value of the average energy recovered from anaerobic digestion of the Toledo WWTP using equation 4.8 for the year 2008.

Table 4.5: Energy recovered from methane - anaerobic digestion model

<table>
<thead>
<tr>
<th>Year 2008</th>
<th>( Q ) mgd</th>
<th>( \text{ER}_{\text{anaerobic}} ) ( 10^4 \text{kWh per day} )</th>
<th>Net Electrical Energy ( 10^4 \text{kWh per day} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>82.43</td>
<td>3.60</td>
<td>2.525</td>
</tr>
<tr>
<td>Feb</td>
<td>109.53</td>
<td>4.79</td>
<td>3.354</td>
</tr>
<tr>
<td>Mar</td>
<td>127.66</td>
<td>5.58</td>
<td>3.910</td>
</tr>
<tr>
<td>Apr</td>
<td>103.90</td>
<td>4.54</td>
<td>3.182</td>
</tr>
<tr>
<td>May</td>
<td>64.10</td>
<td>2.80</td>
<td>1.963</td>
</tr>
<tr>
<td>Jun</td>
<td>66.82</td>
<td>2.92</td>
<td>2.046</td>
</tr>
<tr>
<td>Jul</td>
<td>85.84</td>
<td>3.75</td>
<td>2.629</td>
</tr>
<tr>
<td>Aug</td>
<td>46.36</td>
<td>2.02</td>
<td>1.420</td>
</tr>
<tr>
<td>Sep</td>
<td>57.12</td>
<td>2.49</td>
<td>1.749</td>
</tr>
<tr>
<td>Oct</td>
<td>44.44</td>
<td>1.94</td>
<td>1.361</td>
</tr>
<tr>
<td>Nov</td>
<td>54.53</td>
<td>2.38</td>
<td>1.670</td>
</tr>
<tr>
<td>Dec</td>
<td>86.50</td>
<td>3.78</td>
<td>2.649</td>
</tr>
<tr>
<td>Average</td>
<td>77.44</td>
<td>3.38</td>
<td>2.371</td>
</tr>
</tbody>
</table>

(Note: \( E+03 = 10^3 \))

4.6 Biosolids

4.6.1 Energy Recovered from biosolids

Biosolids are byproducts of domestic and commercial sewage and wastewater treatment plants. They have been referred as “treated sludge” and are used for landfills, food agriculture, and non-food agriculture. Most wastewater treatment plants use multiple
hearth or fluidized bed furnaces for disposal of biosolids using an incineration process. This process represents an opportunity to generate electricity via a steam cycle. Energy recovered from biosolids incineration with electricity generation can be calculated by the following equation 4.9 [21].

\[
ER_{\text{incineration}} = \frac{Q \cdot C_s \cdot HV}{HR}
\]

where, \( ER_{\text{incineration}} \) = energy recovered from biosolids incineration per unit time (kWh/day), \( Q \) = wastewater flow rate (mgd), \( C_s \) = wastewater dry solids content (kg/10^6 gal), \( HV \) = biosolids heating value (kj/kg), \( HR \) = steam electric heat rate (kj/kwh). Table 4.6 shows the average energy recovered from incineration of biosolids at Toledo WWTP for the year 2008 using equation 4.9. Energy recovery from biosolids depends on the quantity of wastewater flow rate per day. A minimum flow rate of 5mgd is (18,900 m^3/day) required to produce biosolids which are necessary to make incineration with electricity generation possible without significant reliance on auxiliary fuel.

Table 4.6: Energy recovered from incineration of biosolids - 2008

<table>
<thead>
<tr>
<th>Year 2008</th>
<th>Q mgd</th>
<th>( ER_{\text{incineration}} ) 10^4 kWh per day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>82.43</td>
<td>7.638</td>
</tr>
<tr>
<td>Feb</td>
<td>109.53</td>
<td>10.15</td>
</tr>
<tr>
<td>Mar</td>
<td>127.66</td>
<td>11.83</td>
</tr>
<tr>
<td>Apr</td>
<td>103.90</td>
<td>9.627</td>
</tr>
<tr>
<td>May</td>
<td>64.10</td>
<td>5.939</td>
</tr>
<tr>
<td>Jun</td>
<td>66.82</td>
<td>6.191</td>
</tr>
<tr>
<td>Jul</td>
<td>85.84</td>
<td>7.953</td>
</tr>
<tr>
<td>Aug</td>
<td>46.36</td>
<td>4.295</td>
</tr>
<tr>
<td>Sep</td>
<td>57.12</td>
<td>5.292</td>
</tr>
<tr>
<td>Oct</td>
<td>44.44</td>
<td>4.118</td>
</tr>
<tr>
<td>Nov</td>
<td>54.53</td>
<td>5.052</td>
</tr>
<tr>
<td>Dec</td>
<td>86.50</td>
<td>8.014</td>
</tr>
<tr>
<td>Average</td>
<td>77.44</td>
<td>7.175</td>
</tr>
</tbody>
</table>
Table 4.7: Biosolids energy estimation parameters

<table>
<thead>
<tr>
<th>Factor</th>
<th>Equation Term</th>
<th>Reported Value</th>
<th>Units</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wastewater dry solids content</td>
<td>Cs</td>
<td>680-1,020</td>
<td>kg/10^6 gal</td>
<td>[22]</td>
</tr>
<tr>
<td>Biosolids heating value (Digested biosolids)</td>
<td>HV</td>
<td>9,000-14,000</td>
<td>kj/kg</td>
<td>[22]</td>
</tr>
<tr>
<td>Steam electric heat rate</td>
<td>HR</td>
<td>10,550</td>
<td>kj/kWh</td>
<td>[23]</td>
</tr>
</tbody>
</table>

4.7 Combined Heat and Power Generation

Combined heat and power (CHP) describes [24, 25, 26] a system that simultaneously or sequentially generates electric energy and utilizes the thermal energy that is normally wasted. Figure 4-9 shows the basic operation of a combined heat and power system. Most of the wastewater treatment plants have an anaerobic digester plant and produce greenhouse gases like methane, CO₂ and NO₂. The digester gas (methane) and landfill gas can be used as a fuel for a turbine or a micro turbine or a fuel cell. The generator converts mechanical energy into electrical energy. The electrical energy is used to operate the plant, and surplus energy is fed back to the grid. The heat produced from the turbine or fuel cell is recovered by a heat recovery unit. The recovered heat is locally used to maintain constant digester heat and also used for space heating purposes. Methane gas is a predominant greenhouse gas compared to CO₂ and NO₂. So the combined heat and power systems reduce greenhouse gases on a large scale because they use large amount of methane as a fuel. The operation of combined heat and power systems is based on water processing capacity, such as the amount of wastewater
processed per day. For example, to produce 100 kW of electricity and 12.5 MMBtu (Million British thermal units per cubic foot) of thermal energy using a combined heat and power system requires an influent rate of 4.5 mgd.

Fortunately, the Toledo Bay Area wastewater treatment plant is processing approximately a daily average of 77.44 mgd [3]. So a combined heat and power system is suitable for the Toledo bay area wastewater treatment plant. A combined heat and power system needs a high capital investment, but its environmental impact is better than any other system, and also it has high operation and maintenance costs.

![Diagram of Typical CHP System Configuration at WWTFs](image)

**Figure 4-9: Individual system components of CHP**

The advantage of a combined heat and power system is onsite power and heat generation, high fuel efficiency, and reduction of greenhouse gas emissions. The overall fuel conversion efficiency of combined heat and power generation system is 70% to 90% [6]. The efficiency calculation of CHP is shown in appendix B. The Northwest Combined
Heat and Power Application Centre [27] play a very important role in the implementation of combined heat and power systems at wastewater treatment facilities.

4.8 Energy Consumption Model for WWTP

The energy model of wastewater treatment plants is a complex one, and no generic models are available to calculate the overall energy value of the wastewater treatment plants. The energy model consists of lighting, motor operation, process operation, heating, and cooling. Studies of the energy estimation of wastewater treatment plants have been performed [5, 6], and the energy value can be estimated based on the daily monitoring of the energy value for longer periods of time. The overall energy value is calculated based on the estimation of processing one million gallons of wastewater per day. Each plant has different capacities and different types of treatments. There are four types of wastewater treatment plants at present in the United States. These are the following

a) Trickling filter treatment plant
b) Activated sludge treatment plant
c) Advanced wastewater treatment plant without nitrification
d) Advanced wastewater treatment plant with nitrification.

4.8.1 Robert Energy Consumption Model for WWTP

Robert (1978) calculated the total energy consumption for municipal wastewater treatment plants [28]. He addressed three major issues of energy calculations: a) energy consumption for the total plant, b) energy consumption for plant operation, and c) recoverable energy from the plant. These energy calculations were based on plant wastewater treatment capacity. The plant capacities were 1 mgd, 10 mgd, and 100 mgd.
(millions of gallons treated per day). Robert (1978) proposed a generic relationship between energy consumption and wastewater treatment capacity for three types of plants [28]. These are a) primary plants, b) high-rate trickling filter plants and, c) activated sludge plants. Total electrical power consumption was approximately expressed for each plant type as follows:

- a) kWh /million gallons = 390 mgd^{-0.15} for primary plants
- b) kWh /million gallons = 700 mgd^{-0.12} for high-rate trickling filter plants and
- c) kWh /million gallons = 1100 mgd^{-0.06} for highly activated sludge plants

Table 4.8 shows the energy calculated by Smith for various treatment capacities of wastewater treatment plants.

### Table 4.8: Total energy consumption of WWTP - Robert approach

<table>
<thead>
<tr>
<th>Energy classifications</th>
<th>1 mgd</th>
<th>10 mgd</th>
<th>100 mgd</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy for total plant (Sewer construction, Plant construction, Electrical energy, chemicals, Digester heating, Building heating, Sludge hauling, Sludge Incineration)</td>
<td>3716 kWh/ mgd</td>
<td>2648 kWh/ mgd</td>
<td>2293 kWh/ mgd</td>
</tr>
<tr>
<td>Energy for plant operation (Electrical energy, Digester heating, Building heating, Sludge hauling, Sludge Incineration)</td>
<td>1448 kWh/ mgd</td>
<td>1350 kWh/ mgd</td>
<td>1319 kWh/ mgd</td>
</tr>
<tr>
<td>Recoverable energy from the plant (Electrical energy, Digester heating, Building heating)</td>
<td>831 kWh/ mgd</td>
<td>764 kWh/ mgd</td>
<td>782 kWh/ mgd</td>
</tr>
</tbody>
</table>

#### 4.8.2 Stilwell Energy Consumption Model for WWTP

Stilwell et al., (2010) calculated the optimal recoverable energy and energy consumption for four types of wastewater treatment plants in the United States [21]. He used two renewable energy resources from the plants. One is biogas from an anaerobic process, and the second is from biosolids. The biosolids is produced by digestion of
wastewater sludge. These two sources can be used for electricity generation by utilization of biogas as a fuel for a gas turbine and incineration of biosolids. The energy consumption and recoverable energy of four types of wastewater treatment plants are given below for various plant capacities:

Table 4.9: Energy consumption and energy recovery of different types of WWTP

<table>
<thead>
<tr>
<th>Plant type</th>
<th>Item</th>
<th>1 mgd plant</th>
<th>5 mgd plant</th>
<th>10 mgd plant</th>
<th>20 mgd plant</th>
<th>50 mgd plant</th>
<th>100 mgd plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Requirements of Trickling Filter Treatment Plant (T1)</td>
<td>Total (kWh/day)</td>
<td>1,811</td>
<td>4,892</td>
<td>8,517</td>
<td>15,005</td>
<td>34,368</td>
<td>67,319</td>
</tr>
<tr>
<td></td>
<td>Energy recovery (from biogas combustion) kWh/day</td>
<td>na</td>
<td>na</td>
<td>2,800</td>
<td>5,600</td>
<td>14,000</td>
<td>28,000</td>
</tr>
<tr>
<td></td>
<td>Net consumption (kWh/day)</td>
<td>1,811</td>
<td>4,892</td>
<td>5,717</td>
<td>9,405</td>
<td>20,368</td>
<td>39,319</td>
</tr>
<tr>
<td>Energy Requirements of Activated Sludge Treatment Plant (T2)</td>
<td>Total (kWh/day)</td>
<td>2,236</td>
<td>6,846</td>
<td>12,032</td>
<td>22,283</td>
<td>52,544</td>
<td>102,824</td>
</tr>
<tr>
<td></td>
<td>Energy recovery (from biogas combustion) kWh/day</td>
<td>na</td>
<td>na</td>
<td>3,500</td>
<td>7,000</td>
<td>17,500</td>
<td>35,000</td>
</tr>
<tr>
<td></td>
<td>Net consumption (kWh/day)</td>
<td>2,236</td>
<td>6,779</td>
<td>8,532</td>
<td>15,283</td>
<td>35,044</td>
<td>67,824</td>
</tr>
<tr>
<td>Energy Requirements of Advanced Treatment Plant without Nitrification (T3)</td>
<td>Total (kWh/day)</td>
<td>2,596</td>
<td>7,864</td>
<td>14,081</td>
<td>26,051</td>
<td>60,822</td>
<td>118,814</td>
</tr>
<tr>
<td></td>
<td>Energy recovery (from biogas combustion) kWh/day</td>
<td>na</td>
<td>na</td>
<td>3,500</td>
<td>7,000</td>
<td>17,500</td>
<td>35,000</td>
</tr>
<tr>
<td></td>
<td>Net consumption (kWh/day)</td>
<td>2,596</td>
<td>7,964</td>
<td>10,581</td>
<td>19,051</td>
<td>43,322</td>
<td>83,814</td>
</tr>
<tr>
<td>Energy Requirements of Advanced Treatment Plant with Nitrification (T4)</td>
<td>Total (kWh/day)</td>
<td>2,951</td>
<td>9,631</td>
<td>17,912</td>
<td>33,514</td>
<td>79,383</td>
<td>155,540</td>
</tr>
<tr>
<td></td>
<td>Energy recovery (from biogas combustion) kWh/day</td>
<td>na</td>
<td>na</td>
<td>3,500</td>
<td>7,000</td>
<td>17,500</td>
<td>35,000</td>
</tr>
<tr>
<td></td>
<td>Net consumption (kWh/day)</td>
<td>2,951</td>
<td>9,631</td>
<td>14,412</td>
<td>26,514</td>
<td>61,883</td>
<td>120,540</td>
</tr>
</tbody>
</table>
Smith and Stillwell did not consider solar, wind, and landfill gas as energy sources for municipal wastewater treatment plants. Therefore, choosing RE and its implementation in the wastewater treatment plant is very important for sustainable plant operation. Also, the RE will contribute to mitigating the energy crises of the next century. Table 4.10 shows the estimated value of energy consumption of four types of WWTP. Toledo WWTP represents a type T4 plant and its average energy consumption and wastewater flow rate Q shown in Table 4.10. The average energy consumption for a 100 mgd plant (T4) is 155,540 kWh per day. Then the average plant energy consumption (kWh per day) for a Q mgd plant can be calculated from equation 4.10. The same procedure is followed for T1, T2, and T3 plant types.

\[
\text{Plant energy consumption (T4)} = \frac{(Q)(155,540)}{100} \quad (4.10)
\]

Table 4.10: Average energy consumption of Bay area WWTP (T4)

<table>
<thead>
<tr>
<th>Year 2008</th>
<th>Q mgd</th>
<th>Electricity Used, (10^4)kWh per day</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>T1</td>
</tr>
<tr>
<td>Jan</td>
<td>82.43</td>
<td>5.549</td>
</tr>
<tr>
<td>Feb</td>
<td>109.53</td>
<td>7.374</td>
</tr>
<tr>
<td>Mar</td>
<td>127.66</td>
<td>8.594</td>
</tr>
<tr>
<td>Apr</td>
<td>103.90</td>
<td>6.995</td>
</tr>
<tr>
<td>May</td>
<td>64.10</td>
<td>4.315</td>
</tr>
<tr>
<td>Jun</td>
<td>66.82</td>
<td>4.498</td>
</tr>
<tr>
<td>Jul</td>
<td>85.84</td>
<td>5.778</td>
</tr>
<tr>
<td>Aug</td>
<td>46.36</td>
<td>3.121</td>
</tr>
<tr>
<td>Sep</td>
<td>57.12</td>
<td>3.845</td>
</tr>
<tr>
<td>Oct</td>
<td>44.44</td>
<td>2.992</td>
</tr>
<tr>
<td>Nov</td>
<td>54.53</td>
<td>3.671</td>
</tr>
<tr>
<td>Dec</td>
<td>86.50</td>
<td>5.823</td>
</tr>
<tr>
<td>Average</td>
<td>77.44</td>
<td>5.213</td>
</tr>
</tbody>
</table>
Chapter 5

Uncertainty and Sensitivity Analysis

Total renewable energy of the WWTP is an arithmetic summation of individual renewable energy sources. These sources are defined as energy models in Chapter 4. Each energy model depends on a particular parameter. These parameters have considerable impact on the total renewable energy estimation of WWTP. For example, Wind and solar energy of the location is directly proportional to wind velocity and solar radiation of that location. Digester energy is a function of the wastewater flow rate (Q), which depends on daily activities of the society. Analyzing the limitations of the parameter of energy models is important for efficient plant energy estimation and plant operation. Uncertainty analysis supports the study of these limitations of energy models [72]. The Crystal Ball® software, owned by the Oracle Corporation, is used to conduct uncertainty analyses of the energy models.

Bhat and Kumar et al. (2008) have demonstrated the Crystal Ball® software in studying the uncertainty and sensitivity in the air quality due to the release of bioaerosols [72]. The same tool is used here to study the uncertainty and sensitivity of the total renewable energy estimation of the WWTP. Crystal Ball® software is an analytical tool, and it
implements a user-friendly interface for forecast and risk analysis of a model. The Crystal Ball® software tool uses a Microsoft Excel spreadsheet as a basic platform to perform simulations on a defined model, which has been replicated in this study [73].

The basic simulation process flows of the Crystal Ball® software are the following [73]:-

i. Define the assumption cell for a given energy model

ii. Assign the probability distribution function

iii. Define the forecasting cell for the energy output

iv. Generate random numbers for the assumption cell using Monte-Carlo technique

v. Output calculation for different input values

vi. Display the results using graphical user interface

5.1 Uncertainty Analysis of Energy Models

Uncertainty can be defined as a measure of the “goodness” of a result [72]. To analyze uncertainty, first we need to define a parameter in assumption cell or input cell using a Microsoft Excel spreadsheet. The uncertain independent variables of the energy models are defined in the assumption cells, such as wind velocity, solar insolation, wastewater flow rate, etc. Forecast cells are output cells that contain one or more assumption cell values to estimate the output of a defined energy model. Here, output of the energy models are assigned in the forecasts cells, such as solar energy, wind energy, digester energy, etc. A detailed list of the forecasting cells and the variables of assumption cells on which they depend is provided in Table 5.1 along with the energy models. Certainty of the energy models is measured by introducing ±5%, ±10%, ±20%, and ±30% errors into the mean energy of the energy models. For example, the average
daily solar energy is $8.44\times10^3$ kWh per day for mean solar insolation of 3.92 watts per meter square. Then certainty is measured between $(8.44\times10^3 - 4.22\times10^2)$ $8.44\times10^3$ kWh per day and $(8.44\times10^3 - 4.22\times10^2)$ $8.86\times10^3$ kWh per day. The $4.22\times10^2$ is the error value, and it is 5% of mean energy value of $8.44\times10^3$ kWh per day. The same procedure is followed for all error values, and these values are shown in Table 5.2.

Table 5.1: Forecasting cells with energy models and their assumption cells

<table>
<thead>
<tr>
<th>Forecasting cell</th>
<th>Energy Models</th>
<th>Assumption cell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Energy</td>
<td>(Conversion factor)x(Wind Velocity) Eq-4.2</td>
<td>Wind Velocity</td>
</tr>
<tr>
<td>Solar Energy</td>
<td>(Conversion factor)x(Solar Insolation) Eq-4.3</td>
<td>Solar Insolation</td>
</tr>
<tr>
<td>Dig1, Dig2, Biosolids</td>
<td>(Conversion factor)x(Wastewater Flow rate) Eq-4.7,4.8,4.9</td>
<td>Wastewater Flow rate</td>
</tr>
<tr>
<td>Landfill Energy</td>
<td>(Conversion factor)x(Methane Gen. rate) Eq-4.6</td>
<td>Methane Gen. rate</td>
</tr>
</tbody>
</table>

Table 5.2: Mean energy and error values for certainty measurement

<table>
<thead>
<tr>
<th>Renewable Energy Source</th>
<th>Mean Energy (kWh/day)</th>
<th>Mean ± 5% error</th>
<th>Mean ± 10% error</th>
<th>Mean ± 20% error</th>
<th>Mean ± 30% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind</td>
<td>$2.89\times10^3$</td>
<td>$2.89\times10^3\pm1.45\times10^2$</td>
<td>$2.89\times10^3\pm2.89\times10^2$</td>
<td>$2.89\times10^3\pm5.78\times10^2$</td>
<td>$2.89\times10^3\pm8.68\times10^2$</td>
</tr>
<tr>
<td>Solar</td>
<td>$8.44\times10^3$</td>
<td>$8.44\times10^3\pm4.22\times10^2$</td>
<td>$8.44\times10^3\pm8.44\times10^2$</td>
<td>$8.44\times10^3\pm1.69\times10^2$</td>
<td>$8.44\times10^3\pm2.53\times10^2$</td>
</tr>
<tr>
<td>Digester1</td>
<td>$3.70\times10^4$</td>
<td>$3.70\times10^4\pm1.85\times10^3$</td>
<td>$3.70\times10^4\pm3.70\times10^3$</td>
<td>$3.70\times10^4\pm7.39\times10^3$</td>
<td>$3.70\times10^4\pm1.11\times10^4$</td>
</tr>
<tr>
<td>Digester2</td>
<td>$2.37\times10^4$</td>
<td>$2.37\times10^4\pm1.18\times10^3$</td>
<td>$2.37\times10^4\pm2.37\times10^3$</td>
<td>$2.37\times10^4\pm4.74\times10^3$</td>
<td>$2.37\times10^4\pm7.10\times10^3$</td>
</tr>
<tr>
<td>Biosolids</td>
<td>$7.16\times10^4$</td>
<td>$7.16\times10^4\pm3.58\times10^3$</td>
<td>$7.16\times10^4\pm7.16\times10^3$</td>
<td>$7.16\times10^4\pm1.43\times10^4$</td>
<td>$7.16\times10^4\pm2.15\times10^4$</td>
</tr>
<tr>
<td>Landfill</td>
<td>$1.81\times10^5$</td>
<td>$1.81\times10^5\pm9.06\times10^3$</td>
<td>$1.81\times10^5\pm1.81\times10^4$</td>
<td>$1.81\times10^5\pm3.62\times10^4$</td>
<td>$1.81\times10^5\pm5.44\times10^4$</td>
</tr>
</tbody>
</table>

The number of trials is chosen based on the consistency of results produced by the Crystal Ball® software. We have examined results for 100, 1,000, 10,000,100,000 and 1000,000 trials. Finally, at 1000000 trials, the simulation results are seen to stabilize.
Therefore, trial number 1000,000 is chosen for all simulations. This is shown in Table 5.3.

Table 5.3: Selection of trials

<table>
<thead>
<tr>
<th>No of Trials</th>
<th>Sim.1</th>
<th>Sim.2</th>
<th>Sim.3</th>
<th>Sim.4</th>
<th>Sim.5</th>
<th>Sim.6</th>
<th>Sim.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>47.01%</td>
<td>47.88%</td>
<td>46.42%</td>
<td>49.06%</td>
<td>43.67%</td>
<td>40.36%</td>
<td>40.14%</td>
</tr>
<tr>
<td>1000</td>
<td>43.51%</td>
<td>43.65%</td>
<td>45.96%</td>
<td>40.30%</td>
<td>46.58%</td>
<td>43.94%</td>
<td>43.89%</td>
</tr>
<tr>
<td>10000</td>
<td>45.14%</td>
<td>45.06%</td>
<td>45.14%</td>
<td>44.49%</td>
<td>44.39%</td>
<td>43.35%</td>
<td>44.22%</td>
</tr>
<tr>
<td>100000</td>
<td>44.68%</td>
<td>44.63%</td>
<td>44.57%</td>
<td>44.45%</td>
<td>44.50%</td>
<td>44.48%</td>
<td>44.37%</td>
</tr>
<tr>
<td>1000000</td>
<td>44.57%</td>
<td>44.59%</td>
<td>44.56%</td>
<td>44.57%</td>
<td>44.56%</td>
<td>44.58%</td>
<td>44.55%</td>
</tr>
</tbody>
</table>

(Note: - Sim.1 means Simulation1)

The Crystal Ball® software always produces a certainty chart, but uncertainty is measured by subtracting the certainty from 100%, and vice versa. One can see the certainty values for each renewable source of the WWTP from Table 5.4. By looking at Table 5.4, one can also calculate the uncertainty value from the certainty value by subtracting the certainty from 100%. Each of the energy models shows different certainty values. Wind energy, which depends on wind velocity, has the highest uncertainty compared to solar energy and digester and biosolids energy; and landfill energy has the least uncertainty when compared to the others. Digester and biosolids energy models are a function of wastewater flow rate (Q). Therefore, renewable energy produced by using digester gas and incineration of biosolids almost has almost the same uncertainty values, and these values are low while comparing the uncertainty of the solar and wind energy models for same error values.
Table 5.4: Assumption cells, assigned probability distribution function and % of certainty of RE models

<table>
<thead>
<tr>
<th>Assumption cell</th>
<th>Probability distribution Function</th>
<th>Distribution Parameters</th>
<th>% of Certainty of RE source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Velocity</td>
<td>Weibull distribution [51,53,54]</td>
<td>Location parameter=2; Scale parameter=8.4; Shape factor=2</td>
<td>2.5 5.05 10.13 15.29</td>
</tr>
<tr>
<td>Solar Insolation</td>
<td>Lognormal distribution [69]</td>
<td>Location=0; Mean=3.94; Standard deviation=2.2</td>
<td>7.37 14.83 29.5 44.52</td>
</tr>
<tr>
<td>Wastewater Flow Rate(Q)</td>
<td>Lognormal distribution [69]</td>
<td>Dig 1 Loc=0; Mean=77.33; Stdev=40.7</td>
<td>7.89 15.68 31.23 46.47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dig 2 Loc=0; Mean=77.33; Stdev=40.7</td>
<td>7.9 15.79 31.30 46.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Biosolids Loc=0; Mean=77.33; Stdev=40.7</td>
<td>7.78 15.58 31.21 46.33</td>
</tr>
<tr>
<td>Methane Gas Generation Rate</td>
<td>Normal distribution [70]</td>
<td>Mean = 1.81x10^5 Standard deviation = 2.39x10^4</td>
<td>12.36 24.45 46.82 65.60</td>
</tr>
</tbody>
</table>

Digester and biosolids energy are available as an internal energy source to most of the WWTP in the United States, and these energy sources can be operated by day and night. These generate a constant source of energy for the plant operation when compared to solar and wind energy. Therefore, digester and biosolids energy are the good choice for the WWTP. The next priority is landfill and solar. Wind energy has the least priority amongst all. Landfill, solar and wind energy are not internal parts of the WWTP, but these can be used as an additional sources of energy for the WWTP where some plants do not have the capacity to process large quantities of wastewater. The following Figures from 5-1 to 5-6 show the certainty chart produced by the Crystal Ball® software.
Figure 5-1: Certainty of wind energy for an error of a) 5%, b) 10%, c) 20% and d) 30% in mean wind energy
Figure 5-2: Certainty of solar energy for an error of a)5%, b)10%, c)20% and d)30% in mean solar energy
Figure 5-3: Certainty of digester1 energy for an error of a) 5%, b) 10%, c) 20% and d) 30% in mean digester1 energy
Figure 5-4: Certainty of digester2 energy for an error of a)5%, b)10%, c)20% and d)30% in mean digester2 energy
Figure 5-5: Certainty biosolids energy for an error of a) 5%, b) 10%, c) 20% and d) 30% in mean biosolids energy
Figure 5-6: Certainty of landfill energy for an error of a) 5%, b) 10%, c) 20% and d) 30% in mean landfill energy.
5.2 Uncertainty and Sensitivity Analysis of Total Energy

Total renewable energy is the summation of solar, wind, landfill, biosolids, and digester energies. This is shown in equation 5.1

\[ E_{\text{Total}} = E_{\text{Solar}} + E_{\text{Wind}} + E_{\text{Landfill}} + E_{\text{Biosolids}} + E_{\text{Digester}} \]  

(5.1)

The WWTP renewable energy can classified into two categories, such as internal renewable energy sources and external renewable energy (RE) sources. Digester and biosolids belong to internal RE category, and solar, wind, and landfill belong to external RE category. Digester energy is estimated using two energy models, which are proposed by Nouri et al. (2006) and Ashlynn et al. (2010). Therefore, we classify the total renewable energy into different combinations to study its uncertainty and sensitivity. These combinations are shown below:

Case1: It consists of all renewable energy models except digester1
Case2: It consists of all renewable energy models except digester2
Case3: It consists of digester1 and biosolids energy models
Case4: It consists of digester2 and biosolids energy models
Case5: It includes solar, wind and landfill energy models

Each energy model depends on a parameter, and sensitivity study is useful to analyze the role of the parameter of the energy models. The Crystal Ball® software calculates the rank correlation and contribution to variance between the assumption cell and the forecast cell. Parameters are defined in the assumption cells, and total energy is defined in the forecast cells. Positive correlation shows a direct proportion, and negative correlation indicates inverse proportion between the assumption cell and forecast cell, making it easier for the user to judge the correlation by merely looking at the sign of the
correlation. The importance of the parameter is measured in terms of a correlation coefficient. The high value of correlation coefficient shows the high importance of the parameter. Certainty is measured for each case by introducing 5%, 10%, and 20% error of total energy value.

In case 1, total energy is the summation of all renewable energy except digester 1. The mean value of total energy is $2.88 \times 10^5$ kWh per day. Case 1 is used to know the certainty value for the total energy due to digester 2. The certainty is measured for case 1 by introducing ±5% ($1.44 \times 10^4$ kWh/day), ±10% ($2.88 \times 10^4$ kWh/day), and ±20% ($5.76 \times 10^4$ kWh/day) errors in total energy with respect to mean value of total energy and their uncertainty and rank correlation; their contributions to variance are shown in Figures 5-7 a, b, c and 5-8 a, b.
c)

Figure 5-7: Certainty of case1 energy except digester1 for an error of a)5%, b)10% and c)20% in mean case1 energy
Figure 5-8: Case1 a) rank correlation, b) contribution to variance

Table 5.5: Case1 certainty chart

<table>
<thead>
<tr>
<th>No</th>
<th>Forecast Cell</th>
<th>% of error</th>
<th>% of Certainty Of case1</th>
<th>Assumption Cell</th>
<th>Rank Correlation</th>
<th>Contribution to Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>$E_{Total} = E_{Wind} + E_{Dig2} + E_{Biosolids} + E_{Landfill} + E_{Solar}$</td>
<td>5%</td>
<td>25.07%</td>
<td>Wind Velocity (F393)</td>
<td>0.21</td>
<td>4.4%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10%</td>
<td>48.44%</td>
<td>Wastewater Flow Rate (B393)</td>
<td>0.95</td>
<td>94.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20%</td>
<td>82.22%</td>
<td>Solar Insolation (D393)</td>
<td>0.01</td>
<td>1.1%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Methane gen.rate (G393)</td>
<td>0.001</td>
<td>-</td>
</tr>
</tbody>
</table>

One can infer from Figures 5-7 and 5-8 and Table 5.5 that contribution of wastewater flow rate to total energy is more than solar, wind and landfill. It has a certainty value of approximately 49% and an error range of ± 10% with respect to mean total energy value.

Case2 includes all the energy except from digester2. An error of ±5% ($1.51 \times 10^4$ kWh/day), ±10% ($3.01 \times 10^4$ kWh/day), and ±20% ($6.02 \times 10^4$ kWh/day) has been introduced in the total energy of $3.01 \times 10^5$ kWh/day. Figure 5-9 a, b, and c shows the measured certainty values for ±5%, ±10%, and ±20% of error values. Also, Figure 5-10 displays the rank correlation and contribution to variance of case2. Case2 is introduced to know the certainty value for the total energy due to digester1.
Figure 5-9: Certainty of case2 energy except digester2 for an error of a) 5%, b) 10% and c) 20% in mean case2 energy
Figure 5-10: Case2 a) rank correlation, b) contribution to variance

Table 5.6: Case2 certainty chart

<table>
<thead>
<tr>
<th>No</th>
<th>Forecast Cell</th>
<th>% error</th>
<th>% of Certainty of case2</th>
<th>Assumption Cell</th>
<th>Rank Correlation</th>
<th>Contribution to Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 2</td>
<td>$E_{Total} = E_{Wind} + E_{Dig1} + E_{Biosolids} + E_{Landfill} + E_{Solar}$</td>
<td>5%</td>
<td>22.72%</td>
<td>Wind Velocity (F393)</td>
<td>0.18</td>
<td>3.5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10%</td>
<td>44.50%</td>
<td>Wastewater Flow Rate (B393)</td>
<td>0.96</td>
<td>95.7%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20%</td>
<td>78.58%</td>
<td>Solar Insolation (D393)</td>
<td>0.09</td>
<td>0.8%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Methane gen.rate (G393)</td>
<td>0.001</td>
<td>-</td>
</tr>
</tbody>
</table>
Case 2 looks like case 1, but there is a small change in rank correlation and variance values. Certainty value is less compared to case 1 and the same trend follows for wind contribution. These are shown in Figures 5-9 and 5-10 and Table 5.6. Digester model 1 and digester model 2 also follow the same trend, but digester model 2 is easier to estimate energy value than digester model 1 due to the simplicity of the calculation [21]. Case 2 has a high certainty of total energy, approximately 73.69% with an error range of ± 20% with respect to the mean energy value. For the same error range, the case 1 certainty value is higher than the case 2 certainty value.

Case 3 is assumed to find the certainty of the internal renewable energy sources of WWTP. It includes digester model 1 and biosolids energy with total energy value of $1.09 \times 10^5 \text{kWh/day}$. An error of ± 5% $(5.43 \times 10^4 \text{kWh/day})$, ±10% $(1.09 \times 10^4 \text{kWh/day})$, and ± 20% $(2.17 \times 10^4 \text{kWh/day})$ has been introduced in the total energy. Certainties have been measured for error values, and these are shown in Figure 5-11 a, b, and c.
Figure 5-11: Certainty of case3 energy for an error of a)5%, b)10% and c)20% in mean case3 energy

Table 5.7: Case3 certainty chart

<table>
<thead>
<tr>
<th>No</th>
<th>Forecast Cell</th>
<th>% error</th>
<th>% of Certainty</th>
<th>Assumption Cell</th>
<th>Rank Correlation</th>
<th>Contribution to Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 3</td>
<td>$E_{\text{Total}}$ + $E_{\text{Dig1}}$ + $E_{\text{Biosolids}}$</td>
<td>5%</td>
<td>7.9%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10%</td>
<td>15.32%</td>
<td>Wastewater Flow Rate (B393)</td>
<td>1</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20%</td>
<td>31.02%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

By examining the Table 5.7 for case3, one can conclude that for case3, the certainty value is low for all error ranges when compared to case1 and case2. As a result, blending
external and internal renewable energy sources assures a high certainty value for total energy.

Case 4 total energy is the summation of digester model 2 and biosolids energy. The certainty is measured by having ±5% (4.77x10^3 kWh/day), ±10% (9.53x10^3 kWh/day), and ±20% (1.91x10^4 kWh/day) error be introduced in total energy of 9.53x10^4 kWh/day. These are shown in Figure 5-12 a, b, and c.
Figure 5-12: Certainty of case 4 energy for an error of a) 5%, b) 10% and c) 20% in mean case 4 energy

Table 5.8: Case 4 certainty chart

<table>
<thead>
<tr>
<th>No</th>
<th>Forecast Cell</th>
<th>% error</th>
<th>% of Certainty</th>
<th>Assumption Cell</th>
<th>Rank Correlation</th>
<th>Contribution to Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 4</td>
<td>( E_{\text{Total}} = )</td>
<td>5%</td>
<td>7.7%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>E_{\text{Dig2}} + E_{\text{Biosolids}}</td>
<td>10%</td>
<td>15.74%</td>
<td>Wastewater Flow Rate (B393)</td>
<td>1</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>20%</td>
<td>30.89%</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

There is not much significant improvement in certainty values of case 4 compared to case 3. Case 4 follows case 3 by having similar values for certainty with the same error.
range. Cases 3 and 4 imply that digester and biosolids are a constant source of internal energy for total energy estimation. To achieve higher certainty value, one can combine the solar, wind, and landfill energy sources with digester and biosolids. Case 1 and case 2 show the highest certainty values for a reasonable range of energy values when integrating external energy sources with internal energy sources of the WWTP. Here, wind, solar, and landfill are considered as external energy sources for the WWTP.

Case 5 is a special case since it is used to measure the certainty of the external sources of WWTP, and an error of $\pm 5\% \ (9.63 \times 10^3 \text{ kWh/day})$, and $\pm 10\% \ (1.93 \times 10^4 \text{ kWh/day})$ has been introduced in the total energy value of $1.93 \times 10^5 \text{ kWh/day}$. Certainty, rank correlation, and variance are measured, and these are shown in Figures 5-13 a, and b and in 5-14 a, and b.

Figure 5-13: Certainty of case 5 energy for an error of a) $5\%$, b) $10\%$ in mean case 5 energy
It shows the highest certainty for an error range of 5%, and 10% compared to other cases. By looking at Table 5.9, one can conclude that wind velocity contributes more variance than solar and landfill. It shows that certainty of total external energy is highly sensitive
to wind parameter than the solar and landfill. Therefore, we need to give more attention for wind energy before its deployment to harvest renewable energy.

However, integration of external and internal renewable energy sources assures high certainty value for an optimal range of energy value. Certainty of case1 and case2 assures that major portion of plant energy can be obtained by integration of internal and external RE sources. Other cases support only less amount of energy for the plant operation. Thus, the Crystal Ball software is helpful to study such analysis using the parameters of energy models.
Chapter 6

Results and Conclusion

Wastewater treatment plant is one of the single largest energy consumers in the USA. Fortunately, these plants are also capable of producing renewable energy on their own. This study addresses various sources of renewable energy and estimates the total renewable energy using existing renewable energy models. Basically, solar, wind, digester, biosolids and landfill are used as renewable energy sources for operation of WWTP. Also, uncertainty and sensitivity analyses are carried out to study the influence of parameters of the energy models.

Wind is not the favorite source of renewable energy for the Toledo WWTP because wind has the lowest certainty amongst all the other available sources. Though solar energy has good certainty, it is difficult to use it as a main source of energy for the entire WWTP operation in Toledo. The reason for this is the low amount of energy produced by solar, which cannot meet daily energy requirement of the plant. This is shown in Figure 6-1 and Table 6.1. The total energy requirement to operate the Toledo WWTP is approximately 44 million units per year. The aggregation of wind energy and solar energy is approximately 15 million units per year. Naturally, these energy sources have discontinuity in producing a constant source of energy. Therefore, blending wind and
solar energy might be useful to operate small ancillary units such as lighting, office buildings etc. However, other sources of renewable energy, such as digester, biosolids and landfill, match perfectly with the plant energy requirements. Sometimes these sources produce more energy than required by the plant. In that case, the additional energy is fed back to the grid to offset the energy bill of the WWTP.

Table 6.1: Certainty values of RE sources and total energy

<table>
<thead>
<tr>
<th>% Certainty of RE sources</th>
<th>Error</th>
<th>±5%</th>
<th>±10%</th>
<th>±20%</th>
<th>±30%</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Renewable Energy Source</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind</td>
<td></td>
<td>2.51</td>
<td>5.05</td>
<td>10.10</td>
<td>15.21</td>
</tr>
<tr>
<td>Solar</td>
<td></td>
<td>7.37</td>
<td>14.83</td>
<td>29.50</td>
<td>44.52</td>
</tr>
<tr>
<td>Dig.1</td>
<td></td>
<td>7.89</td>
<td>15.68</td>
<td>31.23</td>
<td>46.47</td>
</tr>
<tr>
<td>Dig.2</td>
<td></td>
<td>7.90</td>
<td>15.79</td>
<td>31.30</td>
<td>46.34</td>
</tr>
<tr>
<td>Biosolids</td>
<td></td>
<td>7.88</td>
<td>15.58</td>
<td>31.21</td>
<td>46.33</td>
</tr>
<tr>
<td>Landfill</td>
<td></td>
<td>12.36</td>
<td>24.45</td>
<td>46.82</td>
<td>65.60</td>
</tr>
<tr>
<td><strong>Total Energy</strong></td>
<td></td>
<td>25.10</td>
<td>48.52</td>
<td>82.28</td>
<td>-</td>
</tr>
<tr>
<td>Case1</td>
<td></td>
<td>20.70</td>
<td>44.59</td>
<td>78.70</td>
<td>-</td>
</tr>
<tr>
<td>Case2</td>
<td></td>
<td>7.96</td>
<td>15.30</td>
<td>30.90</td>
<td>-</td>
</tr>
<tr>
<td>Case3</td>
<td></td>
<td>7.70</td>
<td>15.76</td>
<td>30.97</td>
<td>-</td>
</tr>
<tr>
<td>Case4</td>
<td></td>
<td>7.96</td>
<td>15.30</td>
<td>30.90</td>
<td>-</td>
</tr>
<tr>
<td>Case5</td>
<td></td>
<td>72.30</td>
<td>88.64</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Figure 6-1: Total RE estimation – 2008

Total energy consumption of WWTP can be replaced by the energy generated from digester and biosolids. See the Table 6.2 and Figure 6-2. This is not reliable during plant maintenance and repair, failure of machines, and unexpected wastewater flow rate etc. The energy from digester and biosolids are proportional to the wastewater flow rate (Q). The daily average of wastewater flow rate of the Toledo WWTP is 77 mgd. The Toledo WWTP is a combined sewer system, and it is subject to high flows as a result of wet weather or snow melt. These effects are modified by the ability of the soil to absorb moisture. It doesn’t take much rain in the winter when the soil is saturated or frozen to cause high flows. In the dry times of late summer, it takes a lot more rain to get high flows. The flow rate and rain data of the year 2008 are shown in Figures 6-3 and 6-4. In such case, the WWTP is always connected to conventional grid for safe and continuous operation.
Table 6.2: Renewable energy estimation - 2008

<table>
<thead>
<tr>
<th>RE Sources</th>
<th>Estimated Energy (10^6 kWh per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>3.1</td>
</tr>
<tr>
<td>Wind</td>
<td>12.7</td>
</tr>
<tr>
<td>Digester Model1-DM1</td>
<td>13.5</td>
</tr>
<tr>
<td>Digester Model2-DM2</td>
<td>8.7</td>
</tr>
<tr>
<td>Biosolids</td>
<td>26.2</td>
</tr>
<tr>
<td>Landfill</td>
<td>66.1</td>
</tr>
<tr>
<td>Plant energy consumption</td>
<td>44.0</td>
</tr>
<tr>
<td>Total energy with DM1</td>
<td>121.7</td>
</tr>
<tr>
<td>Total energy with DM2</td>
<td>116.8</td>
</tr>
<tr>
<td>DM1+Biosolids</td>
<td>39.8</td>
</tr>
<tr>
<td>DM2+Biosolids</td>
<td>34.9</td>
</tr>
<tr>
<td>Solar + wind</td>
<td>15.8</td>
</tr>
</tbody>
</table>

Combined landfill, solar and wind energy value are more (81.9x10^6 kWh per year) compared to plant energy consumption (44 x10^6 kWh per year) and these are uncommon for the most WWTP in the USA. Though landfill, solar, and wind energy sources are favorable to the Toledo WWTP, it requires additional investment to harvest energy from these sources. Figure 6-2 shows the combination of renewable energy estimated during year 2008.
Figure 6-2: Combination of renewable energy estimation

Figure 6-3: Wastewater flow rate - 2008
Finally, more than 80% of WWTP energy can be recovered by the energy generated from digester and biosolids. Some of the WWTP do not have the capacity to process large amount of wastewater. In that case, we can adopt landfill, solar, and wind energy if they are located in the plant periphery. Otherwise plant operation depends on the energy supplied by the local grid. This case study is for Toledo, Ohio, WWTP. This approach can also be applied to other type of WWTP in the USA. Crystal Ball software is used to study the uncertainty and sensitivity of the parameters of renewable energy models. The same tool can be applied to study the uncertainty and sensitivity for more than one WWTP. In this way, we can efficiently estimate the individual plant’s renewable energy in advance and allocate the appropriate financial resources that are suitable to a WWTP and that help it to achieve sustainable plant operation.
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Appendix A

Power Control Unit (Inverter) Efficiency calculation

Inverters are used for DC voltage to AC voltage conversion. According to output voltage form, they could be rectangle, trapezoid, or sine shaped. Large inverters could be connected in parallel when higher powers are required. Inverters connecting a PV system and the public grid are purposefully designed, allowing energy transfers to and from the public grid. The most frequently used three-phase inverter is shown in Figure A-1.

Figure A-1 Three phase inverter
Here, each phase is called single-phase inverter, where each inverter produces an output displaced by 120° with respect to each other. \( T_{A+} (T_{A-}) \), \( T_{B+} (T_{B-}) \), and \( T_{C+} (T_{C-}) \) are called power semiconductor switches. These switches can be thyristor, bipolar junction transistor (BJT), metal oxide semiconductor field effect transistor (MOSFET), and insulated gate field effect transistor (IGBT). Selection of a switch depends on voltage and current blocking capacity, on resistance \( R_{ON} \) of the switch, frequency of operation, and applications. A power semiconductor switch can be operated by gate-switching mechanism. There are two basic gate-switching mechanisms that are commonly used in designing an inverter: a) pulse width modulation (PWM) switching scheme, and b) a square-wave switching scheme [36]. Inverter efficiency is a ratio of AC power and DC power.

DC power

\[
P_{DC} = V_d i_d
\]  

(A.1)

AC power

\[
P_{AC} = V_{\text{RMS}} i_{\text{RMS}}
\]  

(A.2)

Inverter efficiency

\[
\eta = \frac{P_{AC}}{P_{DC}}
\]  

(A.3)

The Maximum efficiency of an inverter at present is 95% to 96% [37].
Appendix B

Combined Heat and Power (CHP) Generation Efficiency calculation

CHP is an efficient and clean approach to generating power and thermal energy from a single fuel source [38].

CHP system

The CHP system includes the unit in which fuel is consumed (e.g. turbine, boiler, engine), the electric generator, and the heat recovery unit that transforms otherwise wasted heat to useable thermal energy.

Total fuel energy input ($Q_{\text{FUEL}}$)

The thermal energy is associated with the total fuel input. Total fuel input is the sum of all the fuel used by the CHP system. The total fuel energy input is often determined by multiplying the quantity of fuel consumed by the heating value of the fuel.

Net useful power output ($W_E$)

Net useful power output is the gross power produced by the electric generator minus any parasitic electric losses - in other words, the electrical power used to support the CHP system. (An example of a parasitic electric loss is the electricity that may be used to compress the natural gas before the gas can be fired in a turbine.)
Net useful thermal output ($\Sigma Q_{TH}$)

Net useful thermal output is equal to the gross useful thermal output of the CHP system minus the thermal input. An example of thermal input is the energy of the condensate return and makeup water fed to a heat recovery steam generator (HRSG). Net useful thermal output represents the otherwise wasted thermal energy that was recovered by the CHP system.

Calculating Total System Efficiency

The most commonly used approach to determining a CHP system's efficiency is to calculate total system efficiency. Also known as thermal efficiency, the total system efficiency ($\eta_0$) of a CHP system is the sum of the net useful power output ($W_E$) and net useful thermal outputs ($\Sigma Q_{TH}$) divided by the total fuel input ($Q_{FUEL}$), as shown below:

$$\eta_0 = \frac{W_E + \Sigma Q_{TH}}{Q_{FUEL}}$$  \hspace{1cm} (B.1)

Figure B-1: Conventional power generation Vs CHP
Calculating effective electric efficiency

Effective electric efficiency calculations allow for a direct comparison of CHP to conventional power generation system performance. Effective electric efficiency ($\xi_{EE}$) can be calculated using the equation below, where ($W_E$) is the net useful power output, ($\Sigma Q_{TH}$) is the sum of the net useful thermal outputs, ($Q_{FUEL}$) is the total fuel input, and $\propto$ equals the efficiency of the conventional technology that otherwise would be used to produce the useful thermal energy output if the CHP system did not exist:

$$\xi_{EE} = \frac{W_E}{Q_{FUEL} - \Sigma(Q_{TH}/\propto)}$$

(B.2)

For example, consider a gas turbine CHP system that produces steam for space heating with the following characteristics: fuel Input = 41 (MMBtu/hr), electric Output = 3 (MW), thermal Output = 17.7 (MMBtu/hr). Using the total system efficiency metric, the CHP system efficiency is 68 percent. Using the effective electric efficiency metric, the CHP system efficiency is 54 percent.
Appendix C

Wind Energy-Power Available in the Wind Spectra

The mass of air passing through area $A_T$ in small time $dt$ is

$$m = \rho_a A_T \, dx \quad \text{(C.1)}$$

Where $\rho_a$ is density of air and $dx$ is distance traveled in time $dt$, so $dx = vdt$, where $v$ is the volume of air parcel. Hence

$$m = \rho_a A_T \, v \, dt \quad \text{(C.2)}$$

The kinetic energy ($E$) of a stream of air with mass $m$ and moving with velocity $V$ is given by

$$E = \frac{1}{2} m V^2 \quad \text{(C.3)}$$

Figure C-1: An air parcel moving towards a wind turbine

Consider a wind rotor of cross sectional area exposed to this wind stream as shown in Figure C-1. The kinetic energy ($E$) of the air stream available for the turbine can be obtained by substituting Eq. C.2 into Eq.C.3. Therefore, the kinetic energy ($E$)
The air parcel interacting with the rotor per unit time has a cross-sectional area equal to that of the rotor ($A_T$) and thickness equal to the wind velocity ($V$). Hence energy per unit time, that is power, can be expressed as

$$P = \frac{1}{2} \rho a A_T V^3$$  \hspace{1cm} (C.5)

From Eq.C.5, we can see that the factors influencing the power available in the wind stream are the air density, area of the wind rotor and the wind velocity. Effect of the wind velocity is more prominent owing to its cubic relationship with the power [41].

**Wind Turbine Power Coefficient**

Theoretical power available in a wind stream is given by Eq. C.5. Nevertheless, a wind turbine cannot extract this power completely from the wind. When the wind stream passes the turbine, a part of its kinetic energy is transferred to the rotor and the air leaving the turbine carries the rest away. Actual power produced by a rotor would thus be decided by the efficiency with which this energy transfer from wind to the rotor takes place. This efficiency is usually termed as the power coefficient or Betz coefficient ($C_p$) [41]. Thus, the power coefficient of the rotor can be defined as the ratio of actual power developed by the rotor to the theoretical power available in the wind. Therefore,

$$C_p = \frac{2P_T}{\rho a A_T V^3}$$  \hspace{1cm} (C.6)

Where $P_T$ is the power developed by the turbine. The power coefficient of a turbine depends on many factors such as the profile of the rotor blades, blade arrangement and setting etc. A designer would try to fix these parameters at its optimum level so as to attain maximum $C_p$ at a wide range of wind velocities.
**Axial Momentum Theory**

The conventional analysis of horizontal axis wind turbine originates from the axial momentum concept introduced by Rankine, which was further improved by Froudes for marine propellers [41]. Ideal flow conditions are considered for this analysis. The flow is assumed to be incompressible and homogeneous. The rotor is considered to be made up of infinite number of blades. Static pressures far in front and behind the rotor are considered to be equal to the atmospheric pressure. Frictional drag over the blades and wake behind the rotor are neglected.

![Axial Stream Tube Model](image)

**Figure C-2: The axial stream tube model**

Consider a wind turbine with rotor of area $A_T$, placed in a wind stream as shown in Figure C-2. Let $A$ and $A'$ be the areas of the sections 1-1, and 2-2 and $V$ and $V'$ are the respective wind velocities at these sections. $V_T$ is the velocity at the turbine section. According to the law of conservation of mass, the mass of air flowing through these sections is equal. Thus:

$$\rho_0AV = \rho_0A_TV_T = \rho_0A'V' \quad \text{(C.7)}$$
The thrust force experienced by the rotor is due to the difference in momentum of the incoming and outgoing wind, which is given by

\[ F = \rho_a AV^2 - \rho_a A'V'^2 \]  

(C.8)

As \( AV = A'V' = A_T V_T \) from (A3.7), the thrust can be expressed as

\[ F = \rho_a A_T V_T (V - V') \]  

(C.9)

The thrust can also be represented as the pressure difference in the upstream and downstream sides of the rotor. Let \( P_U \) and \( P_D \) be the pressure at the upstream and downstream side of the rotor respectively. Therefore:

\[ F = (P_U - P_D)A_T \]  

(C.10)

Applying the Bernoulli’s equation at the sections and considering the assumption that the static pressures at sections 1-1 and 2-2 are equal to the atmospheric pressure \( P \), we get

\[ P + \frac{\rho_a V^2}{2} = P_U + \frac{\rho_a V_T^2}{2} \]  

(C.11)

and

\[ P + \frac{\rho_a V'^2}{2} = P_D + \frac{\rho_a V_T^2}{2} \]  

(C.12)

From Eqs.C11 and C12,

\[ P_U - P_D = \frac{\rho_a (V^2 - V'^2)}{2} \]  

(C.13)

Substituting the above expression for \( (P_U - P_D) \) in Eq.(C.10)

\[ F = \frac{\rho_a A_T (V^2 - V'^2)}{2} \]  

(C.14)

Comparing Eqs.C3.9 and C14 we get

\[ V_T = \frac{(V + V')}{2} \]  

(C.15)

Thus the velocity of the wind stream at the rotor section is the average of the velocities at its upstream and downstream sides.
At this stage, we introduce parameter, termed as the axial induction factor into our analysis. The axial induction factor $a$ indicates the degree with which the wind velocity at the upstream of the rotor is slowed down by the turbine. Thus

$$a = \frac{V - V_T}{V}$$  \hspace{1cm} (C.16)

From Eqs.C.15 and C.16,

$$V_T = V(1 - a)$$  \hspace{1cm} (C.17)

$$V' = V(1 - 2a)$$  \hspace{1cm} (C.18)

As we have seen earlier, the power imparted to the wind turbine is due to the transfer of kinetic energy from the air to the rotor. The mass flow through the rotor over a unit time is

$$m = \rho A_T V_T$$  \hspace{1cm} (C.19)

Hence the power developed by the turbine due to this transfer of kinetic energy is

$$P_T = \frac{1}{2} \rho A_T V_T (V^2 - V'^2)$$  \hspace{1cm} (C.20)

Substituting for $V_T$ and $V'$ from Eqs.C.17 and C.18, we get

$$P_T = \frac{1}{2} \rho_a A_T V^3 4a(1 - a)^2$$  \hspace{1cm} (C.21)

Comparing Eqs.C.21 with the expression for power coefficient in Eq.C.6, we can see that

$$C_p = 4a(1 - a)^2$$ \hspace{1cm} (C.22)

For $C_p$ to be maximum,

$$\frac{dC_p}{da} = 0$$ \hspace{1cm} (C.23)

Thus differentiating Eq.C.22, equating it to zero and solving, we get $a = 1/3$. 

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Substituting for \( a \) in Eq.C.22, the maximum theoretical power coefficient of a horizontal axis wind turbine is \( C_p = 16/27 = 0.59259 \) and the maximum power produced by wind turbine is

\[
P_{\text{max}} = \frac{1}{2} \rho_a A_T V^3 C_p
\]  

(C.24)

This limit for the power coefficient is known as the Betz limit. The Betz limit \( C_p \) is always less than 1.

**Annual Wind Energy Output**

The energy (E) in the wind stream is the product of power and unit time. It is shown in Eqs.C.25

\[
E = P_t = \frac{1}{2} \rho_a A_T V^3 t
\]  

(C.25)

The annual energy output is the product of power in the wind for some period of time (t) and measure of the distribution of wind speed (1.9 for the Rayleigh distributions coefficient, 2 for Weibull distributions coefficient [51, 72] during that time and the conversion coefficient \( C_p \)[42],

\[
AEO = \frac{1}{2} C_p \rho_a A_T V^3 1.9t
\]  

(C.26)

where \( AEO = \) annual energy output in kWh per year, \( t = 8760 \) for one year, \( C_p = 20\% \), \( A_T = \frac{\pi D^2}{4} \) = rotor swept area in square meters, \( V = \) wind velocity in meter per second, \( \rho_a = \) practical air density value = 1.225 kg/m\(^3\), \( D = \) rotor diameter in meters.

To find kilowatt-hours per year, we must divide by 1000. Hence Eqs.C.26 becomes

\[
AEO = \frac{20*1.225*1.9*8760*\pi}{2*4*100*1000} D^2 V^3
\]  

(C.27)

Finally,
AEO = 1.600552 D^2V^3 \quad \text{(C.28)}

The daily energy output is measured in kWh/day and it is shown in Eqs.C.29

DEO = 0.004389 D^2V^3 \quad \text{(C.29)}
Appendix D

Methane Production Rate from Anaerobic Digestion of Wastewater

Anaerobic treatment is utilized for wastewaters as well as for digestion of sludge. The end products of anaerobic degradation are gases, mostly methane (CH\textsubscript{4}), carbon dioxide (CO\textsubscript{2}), and small quantities of hydrogen sulfide (H\textsubscript{2}S) and hydrogen (H\textsubscript{2}) [45]. The anaerobic process consists of two steps: (1) acid fermentation and (2) methane fermentation. In the acid fermentation process, the complex organic compounds in the wastewater are first hydrolyzed to yield smaller molecular units, which in turn are subject to bio oxidation being converted mainly to short-chain organic acids, such as acetic (CH\textsubscript{3}COOH), propionic (CH\textsubscript{3}CH\textsubscript{2}COOH), and butyric (CH\textsubscript{3}-CH\textsubscript{2}-CH\textsubscript{2}-COOH). In methane fermentation process, “methanogenic microorganisms”, which are strictly anaerobic, convert the longer chain acids to methane, carbon dioxide, and organic acids having a shorter carbon chain. The acid molecules are repeatedly broken down yielding finally acetic acid, which is then converted to CO\textsubscript{2} and CH\textsubscript{4}:

\[
\text{CH}_3\text{COOH} \xrightarrow{\text{Methanogenic bacteria}} \text{CO}_2 + \text{CH}_4
\]

Chemical oxygen demand (COD) corresponds to the amount of oxygen required to oxidize the organic fraction of a sample (molecules of wastewater). Biochemical oxygen demand (BOD) is used as a measure of the quantity of oxygen required for oxidation of
biodegradable substrate (organic matter) present in the water sample. The bCOD is biodegradable chemical oxygen demand which is calculated using BOD value (bCOD = 1.6 BOD).

![Figure D-1: Anaerobic digester](image)

The digester shown in Figure D-1 has volume V, input substrate flow rate QS₀ and output substrate flow rate QS. Therefore net substrate of the digester is shown as follows

\[
\text{Net substrate} = \text{Input substrate flow rate} - \text{Output substrate flow rate}
\]

\[
\text{Net substrate} = Q(S₀ - S)
\]

The net substrate in the digester goes through the two step process to generate methane but, yield of methane generation is estimated from the oxygen equivalent of methane (COD). This is shown in the following chemical equation

\[
\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}
\]

1 g mol CH₄ → 2 g mol O₂ → 64 g O₂ → 64 g of COD removed
Thus, if all substrate were converted to CH$_4$, 1/64 g mol of CH$_4$ would be produced per gram of COD removed. The volume of CH$_4$ (liters), measured at standard conditions corresponding to 1/64 g mol of CH$_4$ is

$$\left(\frac{1}{64}\right)(22.4) = 0.35 \text{ liter}$$

Therefore, 0.35 liter of CH$_4$ would be formed per gram of COD removed [45]. The volume of methane generated in the digester is defined in the following equation [46]

$$V_{CH_4} = (0.35)[Q(S_0 - S)]$$

This computation would be correct if all the substrate was converted to methane degradation products, namely CO$_2$ but, part of the substrate is converted to biomass (Cell tissue). If the average molecular formula for the biomass is assumed to be C$_5$H$_7$NO$_2$, the oxygen equivalent to the biomass yield is calculated from the equation shown below:

$$C_5H_7NO_2 + 5O_2 \rightarrow 5CO_2 + NH_3 + 2H_2O$$

$$113 \times 5 \times 32 = 160 \text{ as } 160/113 = 1.42.$$ 

Therefore, 1.42 lb of O$_2$ is required to produce 1 lb of biomass. If $P_X$ is the grams of biomass produced per day then total methane should be estimated by subtracting from the total COD removal that part which is converted to biomass. The value of subtraction is 1.42 $P_X$. Hence, methane generation volume becomes

$$V_{CH_4} = (0.35)[Q(S_0 - S)(10^3 \text{g/Kg})^{-1} - 1.42P_X]$$

Where $P_X$ can be calculated as

$$P_X = \frac{YQ(S_0-S)(10^3 \text{g/Kg})^{-1}}{1+k_d(SRT)}$$

where $V_{CH_4}$ = volume of methane produced at standard conditions, m$^3$/day, 0.35 is the theoretical conversion factor for the amount of methane produced, m$^3$, from the
conversion of 1 kg of bCOD at 0°C, Q = flow rate, m³/day, $S_0$ = bCOD in influent, mg/L, 
$S$ = bCOD in effluent, mg/L, $P_x$ = net mass of cell tissue (biomass) produced per day, 
kg/day. $Y$ = yield coefficient, g VSS (volatile suspended solids)/ g bCOD, $k_d$ = 
enogenous coefficient, d⁻¹ (typical values range from 0.02 to 0.04), SRT = solids 
retention time, day. $(10^3 g/Kg)^{-1} =$ Unit conversion factor for the term $(S_0-S)$ Q into 
Kg/d. The gas produced in the anaerobic process is 2/3 of methane by volume; therefore 
net methane is 65% of $V_{CH_4}$.

Suggested solids retention times for use in the anaerobic digesters are shown in Table 
D.1.

Table D.1: Suggested solids retention times

<table>
<thead>
<tr>
<th>Operating Temperature, 0°C</th>
<th>SRT (min)</th>
<th>SRT (des)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>11</td>
<td>28</td>
</tr>
<tr>
<td>24</td>
<td>8</td>
<td>20</td>
</tr>
<tr>
<td>30</td>
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<td>35</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>40</td>
<td>4</td>
<td>10</td>
</tr>
</tbody>
</table>
Appendix E

Landfill Gas Emission Model-LANDGEM

U.S. Environmental Protection Agency developed a LANDGEM, which is software for quantifying landfill gas emissions, based on the application of Scholl Canyon model and its derivation as follows:

Scholl Canyon Model

Widely used in the estimate of methane gas generation, the model was established by EMCON associate [49]. It is a mere mathematical model and oriented without any consideration of biochemical mechanism that intervenes during LFG formation. It is widely used and seen as the ground foundation of other models. The model does consider neither the first stages nor the second stage of the reaction process. It assumes instead: a negligible lag phase, degradation rate follows the first order kinetic and the methane is assumed to be at the peak at the initial placement.

The starting point is the simple first order degradation reaction applied to the unit mass of waste. The mathematical expression of the degradation process is described as follow

\[-\frac{dL}{dt} = kL\]  \hspace{1cm} (E.1)

\[\frac{dV}{dt} = kL\]  \hspace{1cm} (E.2)

Where \(L\) is the potential volume of methane production in unit volume per mass, \(V\) is the cumulative methane volume produced prior to time \(t\) in unit of volume per mass, and \(k\) is
the constant rate of decomposition in unit of reciprocal of time. Integrating Eq.E.1 and Eq.E.2 gives the following:

\[ L = L_0 e^{-kt} \quad \text{(E.3)} \]

\[ V = L_0 \left[ 1 - e^{-kt} \right] \quad \text{(E.4)} \]

In equation Eq.E.3 and Eq.E.4, \( L_0 \) represents the ultimate potential of methane volume. It becomes clear that \( L_0 \) is the total capacity of the landfill gas production. The total gas production rate is determined by differentiating equation Eq.E.4, which leads to the expression Eq.E.5

\[ \frac{dV}{dt} = - \frac{dL}{dt} = kL = kL_0 e^{-kt} \quad \text{(E.5)} \]

Letting \( R \) be the mass of waste disposed during the year \( t \) considered, and \( Q \) be the total volume of landfill gas production rate, we can write Eq.E.5 as followed:

\[ Q = kRL_0 e^{-kt} \quad \text{(E.6)} \]

Considering the amount of waste disposed in the year \( i \) in unit of mass per year. It is possible to generalize the expression Eq.E.6. For each sub-mass (amount disposed at the year \( i \)) we can write:

\[ Q_i = k_i R_i L_{0i} e^{-k_i t_i} \quad \text{(E.7)} \]

And the general expression takes the form

\[ Q_{LFG} = \sum_{i=1}^{n} k_i R_i L_{0i} e^{-k_i t_i} \quad \text{(E.8)} \]

Where \( n \) is the number of years of waste placement; \( R_i \) the amount of waste disposed in year \( i \) in unit of (Mg), \( k_i \) is the gas generation rate constant account for the amount of waste disposed in year \( i \), in unit of \((y^{-1})\), \( L_{0i} \) is the volume of methane remaining to be produced at \( t = 0 \) for the amount of waste \( i \) (m\(^3\)/Mg), \( t_i \) stands for the age in year of the
waste section placed in the $i^{th}$ year, and $Q_{\text{LFG}}$ is the landfill gas production in unit of $[\text{m}^3/\text{y}]$.

**Formulation and Derivation of LANDGEM**

The originality of the model comes from the aspect that it considers the kinetic of decomposition of different type of organic waste. The mass of methane generated is assumed to be a function of methane generation potential ($L_0$) and the mass of degradable waste deposited. In addition, it assumes that the production of methane is not affected by its concentration. For its complete determination, it is further projected the methane capacity to be 50% and 50% carbon dioxide by volume of the total LFG [50].

Let us write as the starting point the followings equations:

$$\frac{dM_r}{dt} = -kM_r$$  \hspace{1cm} (E.9)

$$\frac{dv}{dt} = kM_rL_0$$  \hspace{1cm} (E.10)

where $M_r$ is the remaining mass of refuse waste at time $t$ in unit of [Mg], $t$ is the time elapsed in unit of [y], $k$ is the first-order rate constant in unit of [y$^{-1}$], $V$ is the cumulative volume of methane generated from the beginning of the degradation to time $t$ in unit of [m$^3$], $L_0$ represents the methane generation potential in unit of [m$^3$/Mg], and $M$ the mass of degradable refuse waste at the initial time in unit of [Mg]. Integrating Eq.E.9 gives

$$M_r = M_e(-kt)$$  \hspace{1cm} (E.11)

Letting $Q = \frac{dv}{dt}$ where $Q$ is the rate of methane production at time $t$ in unit of [m$^3$/y] and inserting (E.11) into in (E.10) yields

$$Q = k L_0 M_e(-kt)$$  \hspace{1cm} (E.12)
Considering the methane capacity to be 50% of the total landfill gas generated, the overall gas production is determined by multiplying equation Eq.E.12 by the factor of 2.

\[ Q_T = 2kL_0 Me^{(-kt)} \]  
\[ (E.13) \]

Owing to the acceptance rate, which represents the periodic dump of waste within the landfill, the gas generation takes the form

\[ Q_T = 2 \sum_{i=1}^{n} k L_0 M_i e^{(-kt_i)} \]  
\[ (E.14) \]

Where \( Q_T \) is the total landfill gas production rate at time \( t \) in unit of \([\text{m}^3/\text{y}]\), and \( M_i \) the mass of waste placed in year \( i \) in unit of \([\text{Mg}]\). Expression Eq.E.13 and Eq.E.14 are applied in the LANDGEM to give the total landfill gas composition and the methane composition.
Appendix F

Parameters Calculation for Weibull Distribution

Different ways were addressed by people to define the wind regime characteristics using probability functions by fitting field data with standard mathematical functions describing frequency distributions. It is established that [52, 53, 54, 55] Weibull distribution can be used to characterize wind regimes in terms of its probability density and cumulative distribution functions. Even though efforts were made to fit the field data with other distributions like Exponential distribution, Gamma distribution [56], and logistic distribution [57], Weibull distribution is well accepted and widely adopted for wind data analysis [58, 59, 60, 61]. Weibull distribution can be characterized by its cumulative distribution function $F(x)$ and probability density function $f(x)$. The most general expression of the Weibull cumulative distribution function [51] is given by the three-parameter Weibull distribution expression such as

$$F(x) = 1 - e^{-\left(\frac{x-\gamma}{\eta}\right)^\beta} \quad (F.1)$$

Where $x \geq 0, \eta > 0, \beta > 0, \text{and } -\infty < \gamma < \infty$. The probability density function is the first derivative of Eq. F.1. So the probability density function for three-parameter Weibull distribution function is the following

$$f(x) = \frac{dF(x)}{dx} = \frac{\beta}{\eta} \left(\frac{x-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{x-\gamma}{\eta}\right)^\beta} \quad (F.2)$$
Where $f(x) \geq 0, x \geq 0, \eta > 0, \beta > 0$, and $-\infty < \gamma < \infty$ and $\beta$ is the shape factor, also known as the Weibull slope, $\eta$ is the scale parameter and $\gamma$ is the location parameter. Both the exponential and Rayleigh distributions are special cases of the Weibull distribution.

Setting $\beta = 1$ in the Weibull density function results in an exponential density function with parameter $\lambda = 1/\alpha$. The Rayleigh distribution is a special case of the Weibull distribution with $\beta = 2$. The two-parameter Weibull cumulative and Weibull distributive distribution function can be derived by setting location parameter $\gamma = 0$ in Eq. F.1 and Eq. F.2. The following equation shows the two-parameter Weibull cumulative distribution function.

$$F(x) = 1 - e^{-(x/\eta)^\beta}$$ (F.3)

The two-parameter Weibull probability density function is

$$f(x) = \frac{dF(x)}{dx} = \frac{\beta}{\eta} \left(\frac{x}{\eta}\right)^{\beta-1} e^{-(x/\eta)^\beta}$$ (F.4)

The $n^{th}$ raw moment for the Weibull distribution is given by the following moment generating function [62]:

$$m_n = \eta^n \Gamma \left(1 + \frac{n}{\beta}\right)$$ (F.5)

Where $n = 1, 2, 3, ...$ and $\Gamma$ is the gamma function $\Gamma(n) = \int_0^\infty e^{-x}x^{n-1}dx$. The mean and variance of Weibull distribution function is calculated by substituing $n = 1$ and $2$ in Eq. F.5.

Mean

$$\text{Mean} = E[x] = m_1 = \eta^{1} \Gamma \left(1 + \frac{1}{\beta}\right)$$ (F.6)

Variance
\[ E[x^2] = m_2 = \eta^2 \Gamma \left( 1 + \frac{2}{\beta} \right) \quad \text{(F.7)} \]

\[ \text{Variance} = E[x^2] - E[x]^2 = \eta^2 \Gamma \left( 1 + \frac{2}{\beta} \right) - \left( \eta \Gamma \left( 1 + \frac{1}{\beta} \right) \right)^2 \quad \text{(F.8)} \]

Similarly, mean and variance for the three-parameter Weibull distribution is as follows:

**Mean**

\[ \text{Mean} = E[x] = \gamma + \eta \Gamma \left( 1 + \frac{1}{\beta} \right) \quad \text{(F.9)} \]

**Variance**

\[ \text{Variance} = E[x^2] - E[x]^2 = \eta^2 \left\{ \Gamma \left( 1 + \frac{2}{\beta} \right) - \Gamma^2 \left( 1 + \frac{1}{\beta} \right) \right\} \quad \text{(F.10)} \]

The \( \beta, \eta, \) and \( \gamma \) parameters have different effect on Weibull probability density function [63, 64]. Actually, some values of the \( \beta \) shape parameter will cause the distribution equations to reduce to other distributions. For example, when \( \beta = 1 \), the pdf of the three-parameter Weibull reduces to that of the two-parameter exponential distribution. The parameter \( \beta \) is a pure number, i.e. it is dimensionless. The following Figure F-1 shows the effect of different values of the shape parameter, \( \beta \), on the shape of the pdf (while keeping \( \gamma \) constant). One can see that the shape of the pdf can take on a variety of forms based on the value of \( \beta \).
Figure F-1: Effect of shape parameter on Weibull probability distribution function

A change in the scale parameter, $\eta$, has the same effect on the distribution as a change of the abscissa scale. Increasing the value of $\eta$ and while holding $\beta$ constant has the effect of stretching out the pdf. Since the area under a pdf curve is a constant value of one, the peak of the pdf curve will also decrease with the increase of $\eta$, as indicated in the following Figure F-2.

- If $\eta$ is increased, while $\beta$ and $\gamma$ are kept the same, the distribution gets stretched out to the right and its height decreases, while maintaining its shape and location.
- If $\eta$ is decreased, while $\beta$ and $\gamma$ are kept the same, the distribution gets pushed in towards the left (i.e. towards its beginning or towards 0 or $\gamma$), and its height increases.
- $\eta$ has the same unit as $X$, such as hours, miles, cycles, actuations, etc.
As the name implies, the location parameter, $\gamma$, locates the distribution along the abscissa. Changing the value of $\gamma$ has the effect of sliding the distribution and its associated function either to the right (if $\gamma > 0$) or to the left (if $\gamma < 0$). The following Figure F-3 shows the effect of location parameter on Weibull pdf.

- When $\gamma = 0$ the distribution starts at time $x = 0$, or at the origin.
- If $\gamma > 0$ then the distribution starts at the location $\gamma$ to the right of the origin.
- If $\gamma < 0$ then the distribution starts at the location $\gamma$ to the left of the origin.
- $\gamma$ has the same units as $x$, such as hours, miles, cycles, actuations, etc.
Three parameters of Weibull pdf are estimated using Eqs.(F.6) and (F.9). In wind energy estimation, $\beta=2$, Rayliegh distribution is used to estimate wind energy potential of the place. Following Table shows the gamma function values for different values of $n$ [65, 66, 67, 68].
Table F.1: Gamma function values for given n

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<th>n</th>
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<th>n</th>
<th>$\Gamma(n)$</th>
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Appendix G

Results

Figure F-1: Solar Insolation - 2008, Toledo

Figure F-2: Solar energy - 2008, Toledo
Figure F-3: Methane generation rate - 2008, Toledo WWTP

Figure F-4: Digester Model1 energy - 2008, Toledo WWTP
Figure F-5: Digester Model 2 energy - 2008, Toledo WWTP

Figure F-6: Biosolids energy - 2008, Toledo WWTP
Figure F-7: Plant energy consumption - 2008, Toledo WWTP

Figure F-8: Landfill energy - 2008, Toledo WWTP
Figure F-9: Wind Velocity

Wind Velocity, h=300m

Wind Velocity (m/s)

Month of the year

Figure F-9: Wind Velocity