Feasibility Study of Sustainable Energy to Power Wastewater Treatment Plants for Islands

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Final thesis for B.Sc. degree
Keilir Institute of Technology
University of Iceland
School of Engineering and Natural Sciences

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UNIVERSITY OF ICELAND

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24 ECTS thesis submitted in partial fulfillment of a
Baccalaureus Scientiarum degree in Energy and Environmental engineering technology

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Keilir Institute of Technology
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Reykjanesbær, May 30, 2014

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Abstract

Municipal wastewater treatment plays a critical role in protecting local water quality and public health. Wastewater treatment is very energy intensive as it involves operation of large motors, drives, pumps and other equipment on a 24 hour-a-day basis. Improving quality of sewage treatment to produce more environmentally safe effluent requires more energy. Conventional energy sources such as oil, gas and coal are non-renewable. The use of fossil fuel has a significant health and environmental impact.

This study discusses the opportunities of using renewable energy sources and self-sufficiency options for wastewater treatment plants (WWTP). The study focuses on applying solar and wind energy, and on site produced biogas to meet the energy requirement and to eliminate emissions from fossil fuel. Two facilities are presented as case study, Kailua, located on the island of Oahu, Hawaii and Hveragerði, located in Iceland. Electricity consumption of the plants was analyzed and the HOMER Energy software was used to evaluate the cost of electricity ($/kWh) of various energy system configurations, each with their own combination of equipment. The objective was to determine the optimal hybrid renewable energy system (HRES). The hybrid system consists of solar PVs, wind turbines and combined heat and power (CHP) unit. A detailed cost and component size evaluation was done for the hybrid system and it showed that renewable energy source can fully and safely power the facilities.

The result suggested that it is economically viable to apply the HRES in Kailua WWTP. Compared with the current electric supply rate (0.29 $/kWh), the HRES unit could reduce the tariff to 0.17 $/kWh. On the other hand, the HRES alternative was not feasible for Hveragerði facility. It costs 1.14 $/kWh to generate electricity, compared to the current rate, 0.12 $/kWh.

Útdráttur

Skolphreinsun í þéttbýli gegnir mikilvægu hlutverki, þar sem óhreinsað skólp getur haft umtalsverð áhrif á umhverfið og heilsu manna. Skolphreinsiferlið er gríðarlega orkufrekt þar sem notaður eru allskonar búnaður og tæki, og ferlið gengur 24 tíma á dag. Það krefst mikla orku að bæta gæði hreinsaðs vatns sem er veitt út í umhverfið. Hefðbundnir orkugjafar eins og olía, jarðgas og kol eru ekki endurnýjanlegir. Notkun jarðefnaeldsneytis stuðlar að losun gróðurhúsalofttegunda.

Verkefnið fjallar um fýsileika þess að gera skolphreinsistöðvar í eyjasamfélögum sjálfbærar með því að nýta endurnýjanlega orku. Megin markmið vekefnisins er að búa til sjálfbæra raforkuframleiðslueiningu til að sjá um rafmagnsþörf skolphreinsistöðva með því að nýta metangas sem myndast í hreinsiferlinum ásamt sólar- og vindorku. Einnig til að útrýma losun gróðuhúsalofttegunda, frá notkun jarðeldsneytis í skolphreinsistöðvum. Tvær skolphreinsistöðvar eru skoðaðar í þessu verkefni, Kailua, staðsett á eyjunni Oahu í Hawaii og Hveragerði á Íslandi. Raforkunotkun stöðvanna var skoðuð og HOMER Energy hugbúnaður var notaður til að hanna raforkuframleiðslukerfi sem samanstendur af solarsellu, rafhlöðu, vindmyllu og efnarafal. Markmiðið var að ákvarða hagkvæmustu einingu og að meta raforkukostnað ($/kWh). Nákvæmt stærðar- og kostnaðarmat var gert fyrir kerfið og niðurstaðan sýndi að endurnýjanleg orka getur séð um rafmagnsþörf skolphreinsistöðva á fullnægjandi og öruggan hátt.

Niðurstaðan sýndi fram á að raforkuframleiðslukerfið getur lækkað raforku kostnað úr 0,29 $/kWh niður í 0,17$/kWh í Kailua. Á hinn bóginn var niðurstan ekki hagkvæm fyrir Hveragerði, raforku kostnaðurinn var 1,14$/kWh miðað við núverandi kostnað sem er 0,12$/kWh.

Dedication

I dedicate my thesis work to my family, especially to my loving children, Maralene and Isabella.

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Abbreviations

WWTP	Wastewater treatment plant
CHP	Combined heat and power
Fig.	Figure
HRES	Hybrid renewable energy system
PV	Photovoltaic
WT	Wind turbine
AC	Alternating current
DC	Direct current
FC	Fuel cell
HOMER	Hybrid Optimization of Multiple Energy Resources
COD	Chemical oxygen demand
BOD_5	5-d Biochemical oxygen demand
O&M	Operations & maintenance
MCFC	Molten carbonate fuel cell
kW	Kilo-watt
kWh	Kilo watt hour
MJ	Mega-joule
NREL	National Renewable Energy Laboratory
LHV	Lower heating value
SS	Suspended solids
Btu	British thermal unit
lb.	Pound (unit)
gal	Gallon
NPC	Net present cost

ft. Foot (unit)

NPC Net present cost

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Firstly, I would like to thank the Keilir Institute of Technology for providing a welcoming, encouraging and flexible study environment that helped me grow in so many ways. I would also like to thank my thesis advisor and everyone who assisted me to conduct this study and write this thesis.

I would like to thank all my fellow graduate students. I had a great three years with you and wish you all best of luck in your future. Lastly, I would like to thank my family for supporting me in any way they could.

1 Introduction

Disposal of untreated wastewater severely threatens the environment. Every year a huge amount of wastewater is discharged directly into watercourse, contaminating rivers and oceans with toxic and harmful substances[1]. Treating wastewater physically, biologically and chemically is vital for the nutrient cycling and maintaining the ecosystem stability. The municipal sewage needs to be effectively treated and managed, with the end goal of reducing and eliminating public health hazards and minimizing the impact of wastewater on the watercourse and its environment. A proper wastewater treatment requires a vast amount of energy [1]. The process is continuous and it involves operation of large, energy intensive equipment on 24 hour-a-day basis. A reliable power supply is important in preventing a power outage, which can have tremendous consequences. It can cause discharge of untreated sewage to the environment or make the sewer system go back by returning wastewater to sinks and toilets. Wastewater flows constantly in and out of the wastewater treatment plant (WWTP) and the operation can not be suspended. The single biggest expense of operating municipal WWTPs comes from electric power use [2]. Operating cost reduction can be achieved through implementation of cogeneration or combined heat and power (CHP[2]) technology.

Medium and a small size WWTPs are discussed as case study. This study considers the possibility of using unconventional energy sources such as, solar energy, wind and biogas to power WWTPs, both safely and economically. A hybrid renewable energy system (HRES) proposed in this paper, is designed to reduce operating cost, eliminate emissions and to achieve energy self-sufficiency for the facilities.

1.1 Objectives

This study aims to assess the feasibility of utilizing renewable energy sources to meet WWTPs electric energy requirement. A hybrid energy system will be designed, including solar PVs, wind turbines (WT) and fuel cells (FC), based on the power consumption analysis. Solar and wind potential energy output will be analyzed with given historical meteorological data from the plant locations. The potential amount of methane (CH_4) produced on site will be estimated. The HOMER (Hybrid Optimization of Multiple Energy Resources) Legacy (v.2.68) energy modeling software is used to assess the cost of electricity (US$/kWh) of various energy system configurations, each with their own combination of components, with the purpose of determining the optimal model with the minimum lifecycle cost.

[1] www.seaweb.org/resources/briefings/toxic.php

[2] www.c2es.org/technology/factsheet/CogenerationCHP

2 Wastewater Treatment

2.1 Overview of Wastewater Treatment

Conventional mechanical wastewater treatment involves a physical and biological process designed to remove organic matter and solids from sewage in order to produce an environmentally safe and non-toxic treated fluids and solids. In municipal wastewater treatment the sewage is carried off through pipe channels and pump stations to centralized wastewater treatment unit. The standard wastewater treatment consists of three stages, preliminary and primary, secondary treatment and disinfection stage. Preliminary steps include flow equalization and removal of materials including, grit, sand, stones and broken glass to protect mechanical components such as pumps and clarifiers from severe wear. In the primary treatment stage, settlement tanks are used to settle and remove organic matters (sludge). The secondary treatment is required to remove suspended and dissolved biological matter by aerobic biological process. The final stage of the treatment requires disinfection to further improve the quality of the effluent before it is discharged to a receiving environment, watercourse [1]. The treatment diagram in Fig. 2.1[3] shows the treatment process in a conventional municipal WWTP.

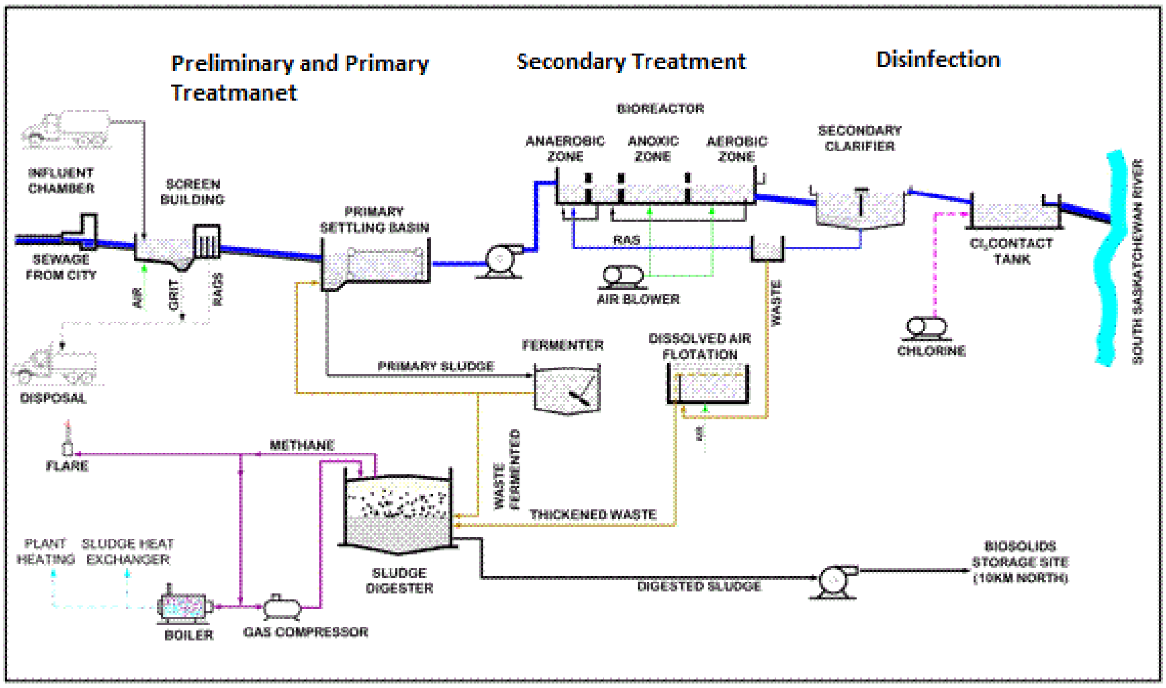

Figure 2.1 Conventional wastewater treatment process

[3] www.saskatoon.ca/DEPARTMENTS/Infrastructure%20Services/Pages/default.aspx.

2.2 Energy Consumption in Wastewater Treatment

Wastewater treatment consumes vast amounts of electricity. Preliminary and primary treatment process is moderately standard among different wastewater treatment facilities while secondary treatment varies depending on factors such as different processing alternatives, inflow rate and concentration of influent. The size of the facilities is another parameter that affects the energy demand as it can be observed in fig. 2.2 [3], that larger facilities with daily inflow over 5000 m^3 a day have less energy demand [3]. In the U.S. wastewater treatment facilities consume an average of 1200 kWh per 3785 m^3 of wastewater treated [4]. In a typical facility electricity is primary utilized for pumping and aeration operations. Fig. 2.3 shows the energy utilization of a standard wastewater treatment system. Overall wastewater pumping is approx. 63% and operations such as screening, grit removal, lighting, gravity thickening and chlorination are 11% of total electricity use [4].

Numerous current facilities have obsolete equipment and processes that are not energy efficient[4]. Also, continuous flow operation makes it complex and difficult to save energy at WWTPs. Therefore, utilizing renewable energy produced on site will have considerable impact on lowering operations cost.

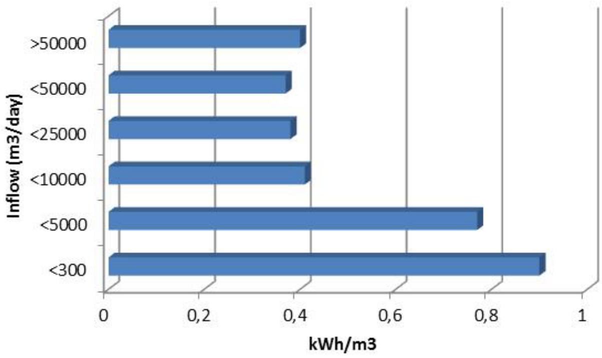

Figure 2.2 Energy demand by influent volume

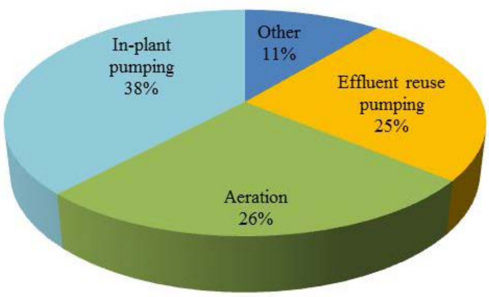

Figure 2.3 Typical wastewater treatment systems energy consumption

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[4] www.dec.ny.gov/chemical/69446.html

3 Hybrid Renewable Energy System Design

3.1 Energy Recovery

The organic materials removed during the different steps of treatment are combined to form a biological sludge that requires further processing before final disposal. Majority of municipal plants use anaerobic biological treatment to stabilize and reduce the volume of sludge. The sludge digestion process involves decomposition of organic and inorganic solids in the absence of air or oxygen. The process is carried out under anaerobic conditions in an enclosed reactor, the anaerobic microorganisms are used to convert the mixture of primary dissolved and suspended sludge to biogas, a mixture of methane and carbon dioxide, water and trace gases [5]. Typically, WWTPs flare the biogas to prevent greenhouse gas emissions.

Biogas released from the anaerobic digestion process can be used for CHP applications. Biogas will be used to fuel the FC to generate electricity and the heat from the FC operation is used to heat the anaerobic digester (reactor). Anaerobic digestion process requires constant thermal energy input to maintain the required digester temperature [6]. There are two optimal operating temperature ranges for the process to produce methane. Mesophilic range is from 29° to 37 °C and the thermophilic range is from 50° to 60 °C [7]. In this study the conventional mesophilic range was considered. In standard WWTPs, anaerobic digesters use a gas-fired boiler combined with a heat exchanger to transfer the heat of combustion to the digested sludge [1]. However, the thermal energy released from the fuel cell can be directly applied to the anaerobic digester through heat exchanger without using gas fired boilers as shown in Fig. 3.1.

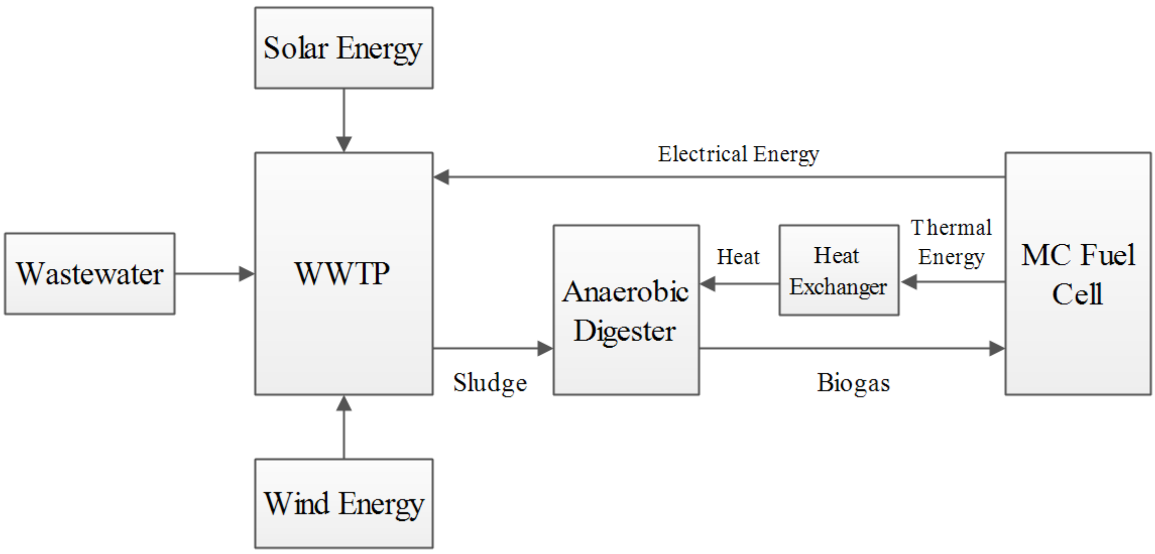

Figure 3.1 HRES energy flow diagram

3.2 Methane Recovery

Biogas from anaerobic digestion process, (Fig. 3.2) [7] is primarily a mixture of methane (CH_4) about 60%-70% and carbon dioxide (CO_2) about 30%-40% [7]. Small amounts of other gases such as, hydrogen sulfide, ammonia and water vapor are also present. Carbon dioxide in biogas decreases its energy content by 22-26 MJ/m^3 [5].

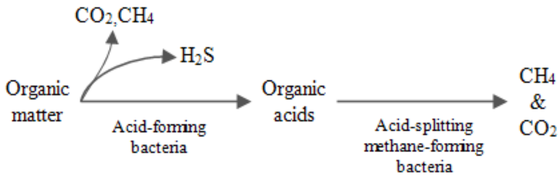

Figure 3.2 Anaerobic digestion process

Energy from biogas is entirely related to methane, which has energy content of 37 MJ/m^3. There are a number of parameters that need to be considered when determining the potential methane recovery from wastewater. The parameters such as, chemical oxygen demand (COD) and 5-d biochemical oxygen demand (BOD_5) are used to measure the concentration of organic compounds in wastewater. The maximum theoretical yield of methane is 0.35 m^3/kg COD removed in an anaerobic process but the value ranges from 0.10 m^3 to 0.35 m^3/kg COD [5].

The rate of methane production depends on the flow rate- and substrate removal and it can be determined by Eq. 3-1.

$$Q_m = Q(S_{T0} - S_{Te})M = QEMS_{T0} \qquad (3\text{-}1)$$

Where Q_m is the quantity of methane per unit time, Q (m^3/day) is influent flow rate, S_{T0} is the total influent COD (kg/m^3, suspended + soluble), S_{Te} is the total effluent COD (suspended + soluble), E is the efficiency factor (conservative value is 0.75) and M is the volume of methane produced per unit of COD removed (conservative value is 0.25 m^3/kg). The BOD_5 (mg/L) value can be used to determine COD value by multiplying BOD_5 by 1.5 [5]. The BOD_5 value from medium strength untreated domestic wastewater is obtained from the table in Appendix A is 200 mg/L. The calculated COD value would be 300 mg/L (200 mg/L*1.5). By employing the parameters above, Eq. 3-1 can also be expressed as

$$Q_m = Q * 0.75 * 0.25\,\frac{m^3}{kg} * 300\,\frac{mg}{L} \qquad (3\text{-}2)$$

3.3 Overall System Architecture

There are three renewable energy sources in the HRES model, solar energy, wind and biogas. The HRES unit simulation is conducted to assess the cost of electricity ($/kWh) of various energy system configurations, each with their own combination of components. The aim is to determine the optimal system configuration. The overall model consists of WTs generating AC power, PVs generating DC power, converters (AC/DC rectifier, DC/AC inverter), a DC fuel cell (FC), DC battery banks and an AC power load required by the facility. Fig. 3.3 [8] represents the system schematic.

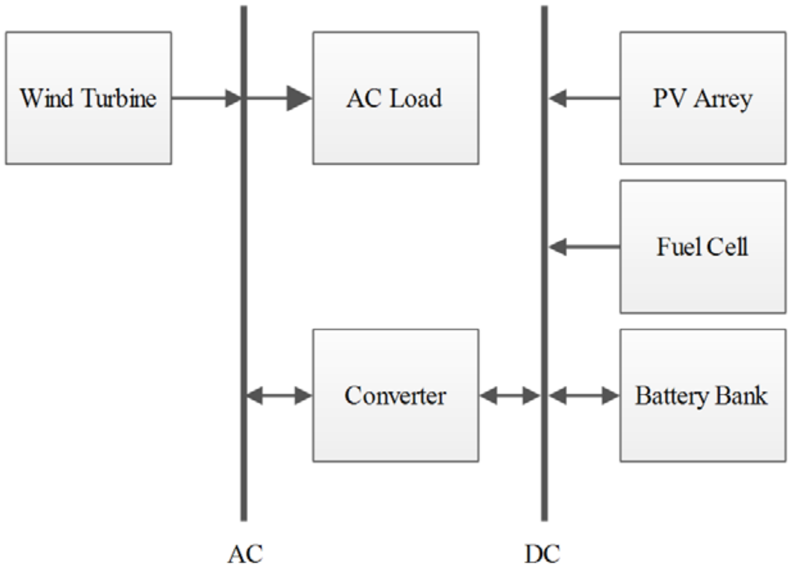

Figure 3.3 The HRES's model

3.3.1 Simulation software

The HOMER Energy software was used to simulate the HRES model. The RETScreen project analysis software was also considered. However, the HOMER was selected as it was more compatible for this project.

HOMER assesses a design options for both off-grid and grid-connected power systems for remote, stand-alone, and distributed generation applications. The program´s optimization and sensitivity analysis algorithms are used to evaluate the economic and technical viability of a numerous technology options and to account for variation in energy resource availability and technology costs. The program simulates both renewable and conventional energy and obtains the optimal cost combination of components that meets electrical and thermal loads. HOMER simulates the operation of a system by making energy balance computations for each of the 8.760 hours in a year[5].

[5] en.openei.org/wiki/SWERA/Analysis_Tools

3.4 Component Parameters and Costs

This section provides commercially available equipment characteristics and estimations for installed cost. The capital costs include the component and installation cost. The estimations are based on typical price levels in the US. The prices are subject to geographical area, market conditions and whether the equipment is used or new.

The following components were used for the system model. The component sizes are selected according to the HOMER optimization. The values are given for both Hveragerði and Kailua WWTP.

3.4.1 Solar PV

Table 3.1 Solar PV - Typical parameters [9]

Parameter	Value	
Size (kW)	30	1500
Lifetime (years)	33	33
Capital ($)	114,570	4,000,500
Operations & maintenance ($/year)	570	30,000
Replacement ($)	114,570	4,000,500

3.4.2 Wind turbine

Table 3.2 Wind turbine - Typical parameter [9]

Parameter	Value	
Size (kW)	10	100
Hub height (m)	40	40
Lifetime (years)	20	20
Capital ($)	63,890	401,900
Operations & maintenance ($/year)	380	3300
Replacement ($)	63,890	401,900

3.4.3 Molten Carbonate Fuel Cell

FCs produce far fewer emissions than conventional fossil fuel power plants and they do not require any emissions control unit to meet current regulations[6]. Table 3.2 provides a typical value of MCFC [10].

Table 3.3 MCFC - Typical parameters

Parameter	Value	
Size (kW)	300	1200
Electrical Efficiency (%)	43	43
Lifetime (hours)	60,000	60,000
Heat Output (MJ/hr)	506.4	2004.6
Capital ($)	1,674,000	6,300,000
Operations & maintenance ($/year)	10,500	38,400
Replacement ($)	1,674,000	6,300,000

3.4.4 Converter

Table 3.4 Converter - Typical parameters [11]

Parameter	Value	
Size (kW)	40	1500
Inverter Efficiency (%)	92	92
Rectifier Efficiency (%)	85	85
Lifetime (years)	20	20
Capital ($)	30,000	1,125,000
Operations & maintenance ($/year)	0	0
Replacement ($)	30,000	1,125,000

[6] www.fuelcells.org/base.cgim?template=benefits

3.4.5 Battery

Table 3.5 Battery - Typical parameters [8]

Parameter	Value
Nominal Capacity (Ah)	1900
Lifetime throughput (kWh)	10,588
Capital ($)	1200[7]
Operations & maintenance ($/year)	0
Replacement ($)	1200

3.4.6 Diesel Generator

Table 3.6 Diesel generator - Typical parameters [12]

Parameter	Value
Size (kW)	50
Lifetime (hours)	60,000
Capital ($)	30,000
Operations & maintenance ($/year)	4750
Replacement ($)	30,000

[7] www.wholesalesolar.com/products.folder/battery-folder/Surretterolls.html

4 Case Study of Kailua Wastewater Treatment Plant

In the following chapters 4 and 5, the HRES model is applied to Kailua and Hveragerði WWTP, and an economical and a technical evaluation is conducted.

4.1 Kailua WWTP Background

Fossil fuel is the main source of electricity generated in Hawaii with over 80% of the total generation. Electricity produced from renewable energy has doubled since 2008, when the Hawaii Clean Energy agreement was signed[8]. Currently, around 20% of the total generation comes from renewable energy sources. Hawaii imports around 90% of its energy and the state has the highest electricity rates among the U.S. states[9].

The Kailua Regional WWTP is located on the northeast shore of the Island of Oahu in Hawaii. It serves the Kailua, Kaneohe and Kahaluu district with the total population of around 80,000[10]. The facility is designed with primary and secondary process to produce a treated effluent with the capacity of 57,000 m^3 per day, with monthly average with a peak hourly maximum of 114,000 m^3/day. Currently, the plant is operating at 45,000 m^3/day.

4.2 Electrical Energy Use

Kailua WWTP´s electricity use is around 93% of its total energy cost. Approximately 75% of the power is used by energy intensive equipment, such as influent, effluent and bio tower pumps, and odor system fans. Operating hours of the equipment ranges from 1000 to 8700 hours a year [13]. The facility´s utility is provided by Hawaii Electric Company. Electricity is delivered through multiple transformers on site. The plant uses five electricity meters to register electricity consumption at the site. Electricity usage data and costs from July 2012 to June 2013 were reviewed. The annual usage of electricity at the site was approximately 7,481,000 kWh, at a cost of around $2,230,000[11]. The monthly average was 623,454 kWh with a daily average load of 20 MWh and 1661 kW peak on a daily basis. The electricity charge rate was $0.29 per kilowatt hour. Table 4.1 provides the monthly electrical use and the charge. The charge includes both consumption and demand costs. Utility providers often charge industrial customers for both demand and consumption[12].

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[8] cca.hawaii.gov/dca/hcei/

[9] www.eia.gov/state/print.cfm?sid=HI.

[10] www.factfinder2.census.gov/faces/nav/jsf/pages/index.xhtml###

[11] Utility usage data and bills received from Kailua WWTP authority.

[12] www.think-energy.net/KWvsKWH.htm

Table 4.1 Kailua WWTP - The monthly electrical energy use and cost

Period	*Electrical Energy Use (kWh)*	*Cost ($)*
Jul. ´12	639,888	200,918
Aug. ´12	557,122	174,926
Sep. ´12	615,732	196,151
Oct. ´12	672,486	208,424
Nov. ´12	642,171	196,773
Dec. ´12	622,127	172,851
Jan. ´13	684,232	187,414
Feb. ´13	586,402	172,995
Mar. ´13	592,274	182,274
Apr. ´13	579,438	174,098
May ´13	648,404	182,451
Jun. ´13	641,173	181,182
Average	623,454	185,871
Total	7,481,449	2,230,463

The monthly electrical peak load profile is shown in Fig. 4.1 [8]. There are no evident seasonal peaks in the power load since the plant operates at constant flow and the process is continuous.

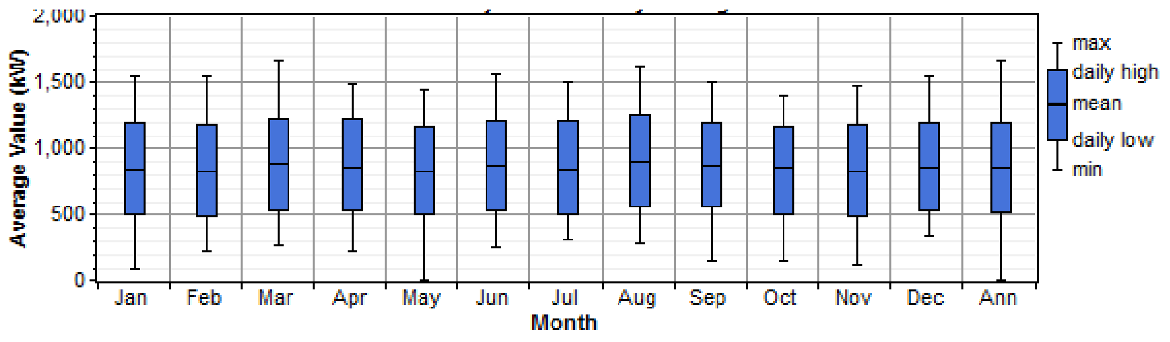

Figure 4.1 The Kailua WWTP´s typical monthly electrical load profile

4.3 Renewable Energy Analysis

The potential solar and wind energy output for the island of Oahu is analyzed with historical meteorological data retrieved from the National Renewable Energy Laboratory (NREL) [14]. The potential amount of biogas generation from the WWTP is estimated by the wastewater influent flow rate.

4.3.1 Wind Energy

The annual average wind speed of the island of Oahu reaches 6.8 m/s. Fig. 4.2 [8] shows the monthly average wind speed with daily mean, high and low value for the twelve-month period. The wind speed is measured 50 m above ground.

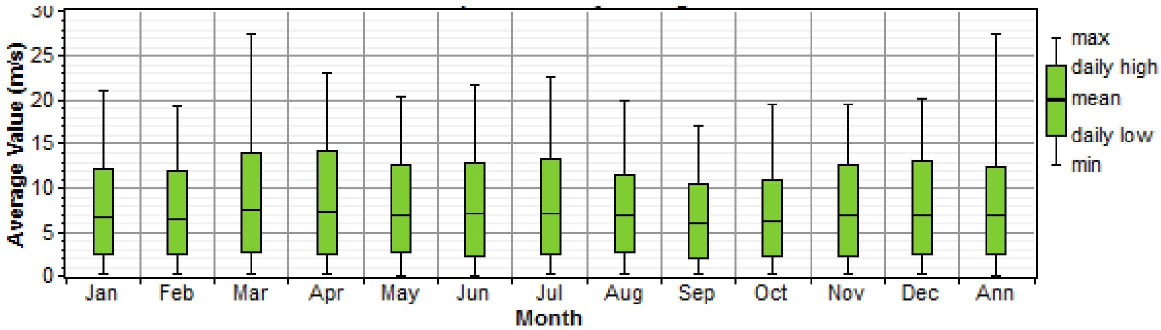

Figure 4.2 Oahu, HI - The wind speed monthly averages

4.3.2 Solar Energy

The solar resource available on the island of Oahu can be observed in Fig. 4.3 [8] with a daily average solar radiation and the clearness index for the twelve-month period. The annual average global solar radiation is 5.9 kWh/m^2 a day. The clearness index is equal to the global solar radiation on the surface of the earth divided by the extraterrestrial radiation at the top of the atmosphere. It is the amount of the extraterrestrial solar radiation that makes it through to the Earth´s surface[13].

[13] www.support.homerenergy.com/index.php?/Knowledgebase/Article/View/203/0/10045---clearness-index-in-homer

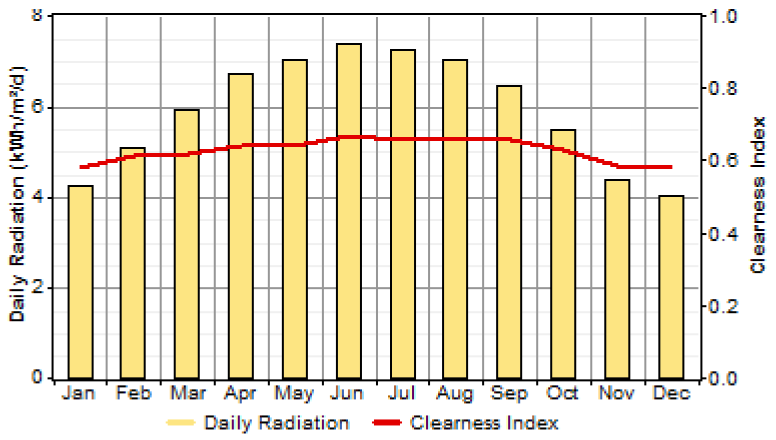

Figure 4.3 Island of Oahu - The global horizontal solar radiation and the clearness index

4.3.3 Methane Gas Analysis

The volume of daily methane production at the Kailua WWTP is determined using Eq. 3-2. The current flow rate at the WWTP is 45,425 m^3 a day.

$$45425\frac{m^3}{day} * 0.75 * 0.25\frac{m^3}{kg} * 300\frac{mg}{L} * \frac{1kg}{10^6 mg} * \frac{1000L}{1m^3} = 2555.16\frac{m^3}{day} \quad (4\text{-}1)$$

The annual source of methane is

$$2555.16\frac{m^3}{day} * 365 = 932{,}632\frac{m^3}{year} \quad (4\text{-}2)$$

4.4 System Architecture

4.4.1 Simulation Inputs and Constraints

The HRES unit is required to serve a plant operating with the load of 20 MWh and 1661 kW peak load on a daily basis. For proper configuration, the following component sizes are considered in the system simulation

- PVs from 10 kW to 2000 kW
- WTs from 10 kW to 1650 kW
- Converters from 300 kW to 2000 kW
- FCs, 300 kW and 1200 kW

A new energy source was added to the system simulation, methane (CH_4) with LHV of 50 MJ/kg and density of 0.66 (kg/m^3)[14].

The system was configured to utilize a maximum of 932,000 m^3 of methane a year, according to the plant´s annual production capacity, (Eq. 4-2).

[14] www.webbook.nist.gov/chemistry/

4.4.2 System Layout

According to the HOMER simulation, considering both economic and technical viability, it suggested an optimal HRES model consisting, 10 units of 100 kW WT, 1500 kW solar PV arrays, a 1500 kW converter, a 1200 kW fuel cell and battery banks with 1500 units with 1900Ah each. The HRES model is designed with a single primary AC power load of 20 MWh/day with a daily peak of 1661 kW[15]. A visual representation of the system model can be seen in Fig. 4.4 [8].

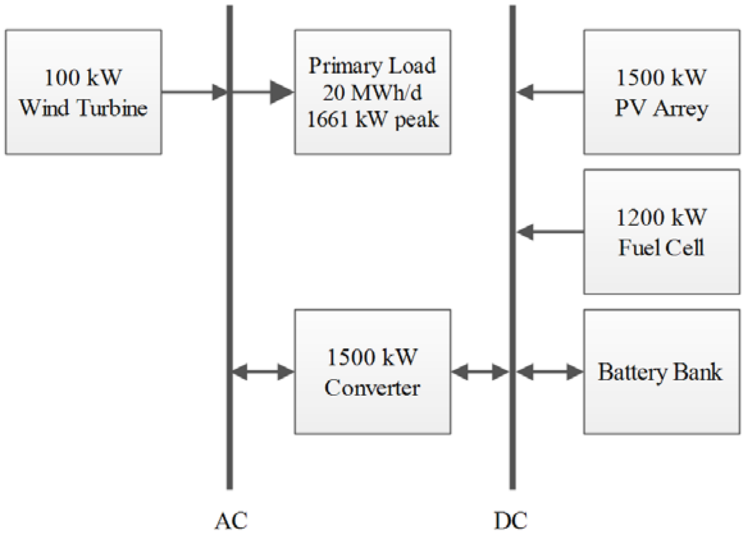

Figure 4.4 Kailua WWTP - The HRES unit layout

4.5 Electricity Production

The system simulation showed that the system will be producing 9,325,636 kWh/year, which covers the annual power load for Kailua WWTP, 7,481,449 kWh/year. PV share in electricity generation is approx. 29% (2,710,003 kWh), WT share is 33% (3,048,186 kWh) and the FC with the highest share of 38% (3,567,447 kWh). FC is consuming 918,445 m^3 of methane a year which is 98% of the plant´s annual generation capacity of methane, 932,632 m^3. Electricity generation ratio by components is shown in Fig. 4.5. The total electricity generated exceeds the load by 1,844,190 kWh, which indicates the system is producing more electricity than it can use. This can occur when the batteries can´t absorb all the excess electricity or when the AC/DC conversion rate is insufficient. For example, if PV on the DC bus supplies an AC load and the PV is producing more electricity than the inverter can convert[16]. However, HOMER Energy selects the most viable system, it is usually expensive to capture and store excess electricity for later use, HOMER evaluates

[15] Utility usage data and bills received from Kailua WWTP authority.

[16] www.support.homerenergy.com/index.php?/Knowledgebase/Article/View/259/0/10085---excess-electricity-in-homer

that there is no value to excess electricity, but also it evaluates the cost of avoiding it[17]. The results from HOMER simulation can be seen in Appendix E.

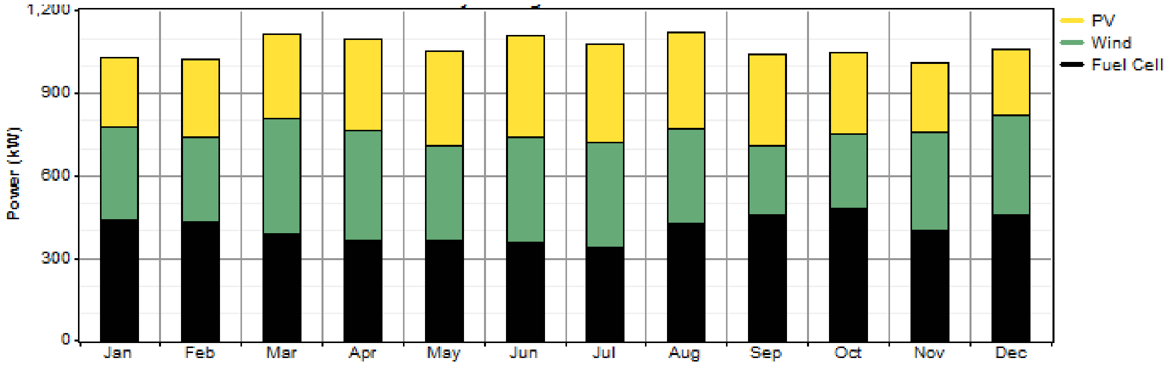

Figure 4.5 Kailua WWTP - The monthly average electric production

4.6 Digester Heating Requirements

The overall heat required for digester include, the amount of heat required to raise the incoming sludge to digestion tank temperature and the heat loss from digester tank through floors, walls and roofs by conduction. The mass of primary sludge needs be to evaluated, in order to estimate the heat required for the sludge on a daily basis [6].

4.6.1 Mass of Sludge per Day

Suspended solids (SS) is a vital characteristics of wastewater, the volume of sludge produced in a treatment process is directly associated with the total suspended solids present in the wastewater [6]. SS are small solid particles which remain in suspension in water as a colloid or due to the motion of the water[18]. The primary treatment process (Fig. 1) removes approx. 60% of the suspended solids [1]. The SS concentration in primary sedimentation effluent flow is estimated by Eq. 4-3 [15]. The SS value (250mg/L) from medium strength untreated domestic wastewater is obtained from the table 13 in Appendix B.

That gives

$$SS_{primary\ effluent} = (1 - 0.60) * 250\frac{mg}{L} = 100\frac{mg}{L} \qquad (4\text{-}3)$$

[17] support.homerenergy.com/index.php?/Knowledgebase/Article/View/158/0/10310---wasted-electricity-production

[18] camblab.info/wp/index.php/what-is-suspended-solids/

The mass of primary sludge produced per day, as dry solids at given flow rate is estimated by Eq. 4-4, where $^{\Delta}SS$ indicates the difference between the SS value from untreated domestic wastewater from section 4.6.1 and the SS value form Eq. 4.3. The current flow rate at the WWTP is 4.5425*10^7 L/day.

$$SS_{dry\,mass} = Q * {}^{\Delta}SS \tag{4-4}$$

That gives

$$SS_{dry\,mass} = 4.5425 * 10^7 \frac{L}{day} * (250 - 100) \frac{mg}{L} * \frac{1kg}{10^6 mg} = 6814 \frac{kg}{day} \tag{4-5}$$

The mass of primary sludge produced per day, as wet sludge is estimated in Eq. 4-6. The typical value for solid concentration in sludge is 6% by weight and the specific gravity of sludge is 1.02 kg/L [6].

Accounting for 6% solids by weight

$$SS_{wet\,mass} = 6814 \frac{kg}{day} * \left(\frac{100}{6}\right) \% = 113567 \frac{kg}{day} \tag{4-6}$$

That gives the sludge flow of

$$Q_{sludge} = \frac{113567 \frac{kg}{day}}{1.02 \frac{kg}{L}} = 111340 \frac{L}{day} \tag{4-7}$$

Eq. 4-7 is converted to lb/day, density of sludge is 8.5 lb/gal [16].

$$111340 \frac{L}{day} * \frac{1gal}{3.785L} * 8.5 \frac{lb}{gal} = 250037 \frac{lb}{day} * \frac{0{,}453kg}{1lb} = 113267 \frac{kg}{day} \tag{4-8}$$

4.6.2 Heat Requirements of Digesters

The heat required for sludge can be computed by Eq. 4-9. The specific heat of sludge is 1 Btu/lb * °F [6]. The mean annual temperature of wastewater ranges from 10 to 21.1°C, the typical value is 15.6°C (60°F). The temperature of the sludge contents in digester ranges from 29 to 37°C (mesophilic), the conservative value is 32°C (90°F) [6].

$$250037 \frac{lb}{day} * (90 - 60)°F * 1 \frac{Btu}{lb} °F = 7.501 * 10^6 \frac{Btu}{day} * \frac{1MJ}{947.8Btu} = 7914 \frac{MJ}{day} \tag{4-9}$$

The heat loss from digester tanks was determined, detailed calculations have been made and can be seen in Appendix A. The WWTP is currently operating with four digester tanks and the total heat loss from the digesters was 6172 MJ/day.

The total heat required for the digesters = the heat loss from digester tanks and the heat required for sludge.

That gives

$$(6172 + 7914) \frac{MJ}{day} = 14086 \frac{MJ}{day} \tag{4-10}$$

4.6.3 Heat Recovery from Fuel Cell

The high operating temperature of the FC, around 648°C gives advantage of recovering high quality heat. The heat recovery from the FC can be determined by multiplying heat output of FC by its operating hours a day. The FC´s heat output is 2004.6 MJ/hr. (from table 3.3) and it will be operating approximately 11 hours a day according to the system simulation. Eq. 4-11 provides the heat recovery from the FC per day.

$$2004.6\frac{MJ}{hr} * 11\frac{hr}{day} = 22050\frac{MJ}{day} \qquad (4\text{- }11)$$

The heat recovered from the FC technically covers the thermal energy required for the digesters which is 14086 MJ/day.

4.7 Results and Discussion

The system simulation assessed various scenarios, including combination of PV - WT, PV - FC, WT - FC and PV - WT - FC. The optimal result suggested that the application of the PV-WT-FC unit in Kailua WWTP is economically the most viable. Compared with the current electric supply rate (0.29 $/kWh), the HRES unit could reduce the tariff to 0.17 $/kWh.

As it can be observed from Table 4.2, around 63% of the heat from the FC is being utilized to meet the digester heat load. The excess heat from the FC can be used for space heating and CHP applications by combining the HRES unit with micro-turbine to generate additional electricity.

Table 4.2 Kailua WWTP - The overall HRES unit summary

	HRES unit
Flow at the WWTP (m^3/day)	**45,425**
Heat requirement for sludge (MJ/day)	**6172**
Heat loss from digesters (MJ/day)	**7914**
Heat potential from FC (MJ/day)	**22,050**
% of heat used for digester heat load	**63**
CH_4 produced on site (m^3/year)	**932,632**
CH_4 used for electricity generation (m^3/year)	**918,445**
Cost of electricity present ($/kWh)	**0.29**
Cost of electricity with HRES Unit ($/kWh)	**0.17**

The system is considered with a project lifetime of 25 years and with an annual real interest rate of 2%[19]. The most economically feasible system was selected with the lowest net present cost (NPC) of $28,497,568 from the system optimization results. The capital investment cost for the system is $17,244,500. The component replacement, maintenance and operation cost is estimated at $17,493,428. Also, $6,240,359 can be salvaged at end of project life time. The operating cost of the system is about $510,965 a year. Compared to the current tariff the WWTP is on ($0.29), the optimized system levelized cost of energy is $0.17 kWh. HOMER determines the cost of energy ($/kWh), by computing the total annualized cost, which is the NPC times the capital recovery factor[20]. The total annualized cost is then divided by the total electric load served (kWh/year).

Table 4.3 provides the overall cost breakdown. The cost of components that are present in the WWTP such as, heat exchangers and digesters are not evaluated. The results from HOMER simulation can be seen in Appendix E.

Table 4.3 Kailua WWTP – HRES unit cost breakdown summary

Component	*Capital ($)*	*Replacement ($)*	*O&M ($)*	*Fuel ($)*	*Salvage ($)*	*Total ($)*
PV	4,000,500	0	660,695	0	-756,234	**3,904,961**
WT	4,019,000	3,293,750	726,764	0	-2,350,418	**5,689,096**
Fuel Cell	6,300,000	5,425,083	3,376,837	0	-1,651,842	**13,450,080**
Batteries	1,800,000	3,088,311	0	0	-823,935	**4,064,376**
Converter	1,125,000	921,988	0	0	-657,930	**1,389,058**
System	**17,244,500**	**12,729,131**	**4,764,297**	**0**	**-6,240,359**	**28,497,566**

[19] www.datamarket.com/data/set/1497/real-interest-rate#!ds=1497!gad=3k.y.v.1r.4g.2n&display=line.

[20] www.investopedia.com/terms/c/capital-recovery.asp

Fig. 4.6 presents the cash flow summary of the system components by NPC. FC has the highest cash flow share over project lifetime with 47% followed by WT with 20%.

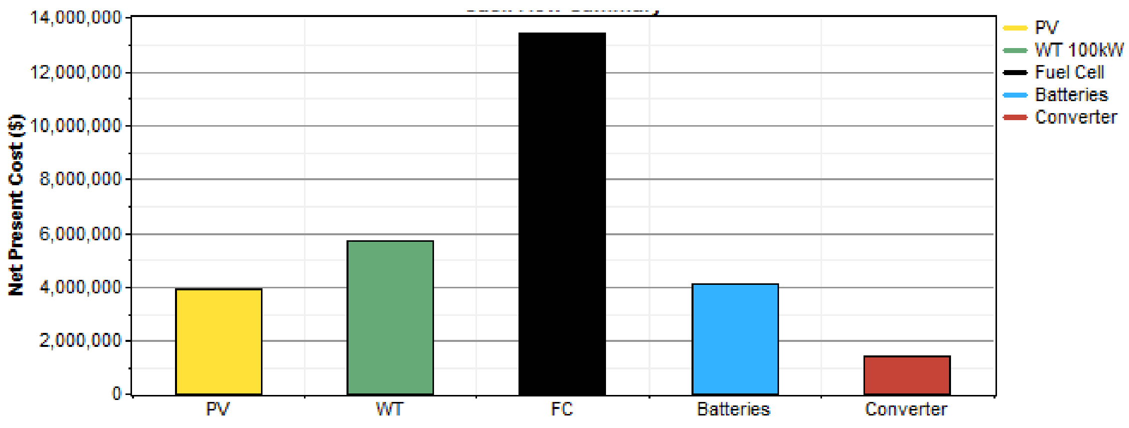

Figure 4.6 Kailua WWTP - The cash flow summary

5 Case Study of Hveragerði Wastewater Treatment Plant

5.1 Hveragerði WWTP Background

The town of Hveragerði is a small community located in the south of Iceland, with a population of 2300[21]. Its sewage is treated by primary and secondary process before it´s discharged to the nearby river. The Hveragerði WWTP is situated in the south of the town. It is operating at the flow rate of 2400 m^3/day, with a daily high of 3600 m^3/day. The plant was built 12 years ago and the equipment inspection at the site is done every four years. The annual operating budget is $213,000 and 8.5% of it is spent on electric energy [17].

5.2 Electrical Energy Use

Hveragerði WWTP´s utility is provided by Reykjavík Energy. Electricity consumption records and costs from 2013 were reviewed. Annual usage of electricity at the site was approximately 149,200 kWh, at a cost of around $18,000. The monthly average was 12,432 kWh, with a daily average load of 409 kWh and 46 kW peak on a daily basis. The electricity tariff was $0.12 per kilowatt hours. The monthly electrical use and the total charge are provided in Table 5.1.

Table 5.1 Hveragerði WWTP - Monthly electrical energy use and cost

Period	*Electrical Energy Use (kWh)*
January ‘13	13,136.9
February	11,975.5
March	12,503.9
April	11,095.2
May	12,219.2
June	12,504.3
July	13,453.8
August	13,095.3
September	12,563.5
October	12,315.7
November	12,122.3
December	12,200.0
Average	12,432.1
Total	149,185.6
Total cost	$18,000

[21] www.hveragerdi.is/English/Hveragerdi/

Figure 5.1 [8] provides the monthly electrical peak load profile based on the data provided by Hveragerði WWTP.

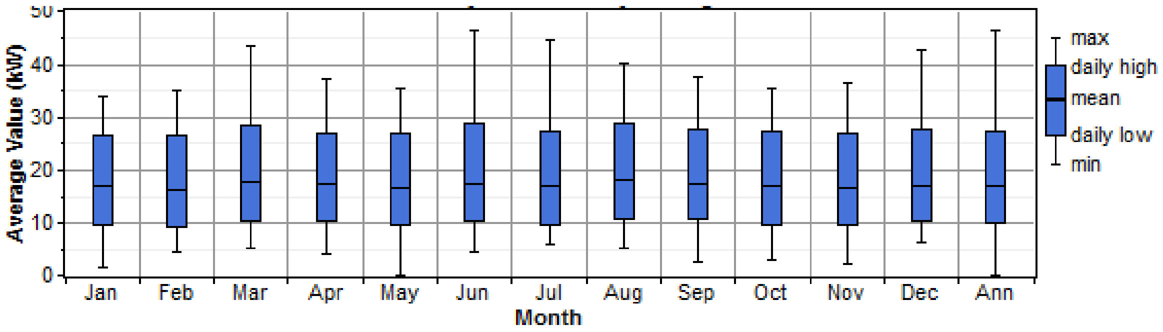

Figure 5.1 Hveragerði WWTP - The typical monthly electrical peak load profile

5.3 Renewable Energy Analysis

The solar and wind potential energy output for the south of Iceland is based on the historical meteorological statistics from the NREL [14]. The potential amount of biogas generation from the WWTP is estimated by the wastewater influent flow rate as mentioned above.

5.3.1 Wind Energy

The wind potential of Iceland ranks among the highest in the world [18] with annual wind velocity of 8.8 m/s (64.00N Lat.). Figure 5.2 [8] shows the monthly average wind speed measured 50 m above ground for the twelve-month period. There are visual peak months from December to March. with a daily high value of 20 m/s.

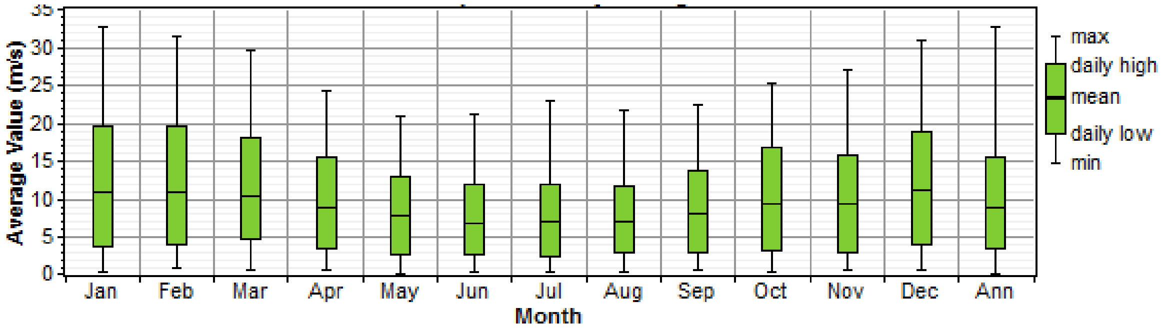

Figure 5.2 South of Iceland - The wind speed monthly averages

5.3.2 Solar Energy

The annual average global solar radiation in the south of Iceland is 5.9 kWh/m^2 a day. Figure 5.3 [8] shows the daily average radiation and the clearness index for the twelve-month period. As can be observed, the solar energy potential is notably low during the winter seasons.

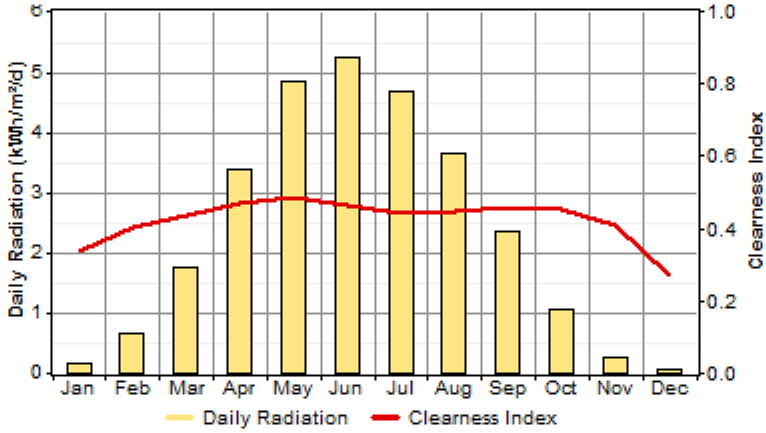

Figure 5.3 South of Iceland - The global horizontal solar radiation and the clearness index

5.3.3 Methane Gas Analysis

The volume of methane potential at the Hveragerði WWTP is determined using Eq. 3-2. The current flow rate at the WWTP is 2400 m^3/day.

$$2400\,\frac{m^3}{day} * 0.75 * 0.25\,\frac{m^3}{kg} * 300\,\frac{mg}{L} * \frac{1kg}{10^6 mg} * \frac{1000L}{1m^3} = 135\,\frac{m^3}{day} \qquad (5\text{-}1)$$

The annual source of methane is then:

$$135\,\frac{m^3}{day} * 365 = 49275\,\frac{m^3}{year} \qquad (5\text{-}2)$$

5.4 System Architecture

5.4.1 Simulation Inputs and Constraints

The HRES unit is required to power a plant operating with the load of 409 kWh and 46 kW peak load on a daily basis. The following component sizes are considered in the system simulation

- PVs from 10 kW to 100 kW
- WTs from 10 kW to 50 kW
- Converters from 10 kW to 100 kW
- FC, 300 kW

Utilization of the methane on site is limited to 49,000 m^3 a year according to the plant´s annual production capacity, (Eq. 5-2).

5.4.2 System Layout

The optimal HRES configuration includes a, 70 kW solar PV array, a 40 kW converter and battery banks with 250 units with 1900Ah each. The HRES model is designed with a single primary AC power load of 409 kWh a day with a daily peak of 46 kW. A graphical representation of the system model can be seen in Fig. 5.4.

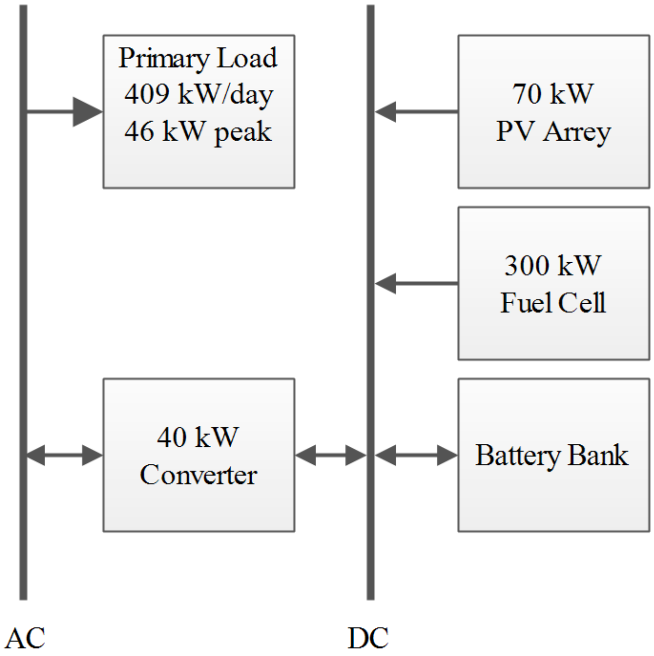

Figure 5.4 Hveragerði WWTP - The HRES unit layout

5.5 Electricity Production

The system simulation shows that the PV and FC combined will be producing 200,055 kWh/year, with PV 85,938 kWh (43%) and FC with 114,117 kWh (57%). The generated electricity covers the annual load of Hveragerði WWTP, 149,185 kWh/year. The system utilizes 47,382 m^3/year of methane produced on site, which is 96% of the plant´s annual generation capacity of methane, 49,275 m^3. Electricity generation ratio by components is shown in Fig. 5.5.

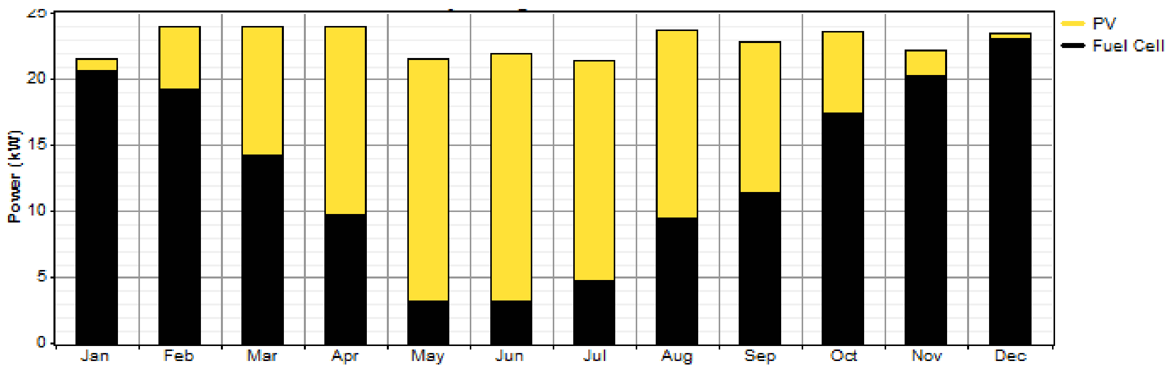

Figure 5.5 Hveragerði WWTP - The monthly average electric generation

5.6 Digester Heating Requirements

5.6.1 Mass of Sludge per Day

The SS concentration in primary treatment effluent flow estimated by Eq. 4-3 [15] is 100 mg/L.

The mass of primary sludge produced per day, as dry solids at given flow rate is determined by Eq. 4-4. The current influent flow rate at the WWTP is 2.4*10[6] L/day.

That gives

$$SS_{dry\ mass} = 2.4 * 10^6 \frac{L}{day} * (250 - 100) \frac{mg}{L} * \frac{1kg}{10^6 mg} = 360 \frac{kg}{day} \quad (5\text{-}3)$$

The mass of primary sludge produced per day, as wet sludge is estimated using Eq. 4-6. The typical value for solid concentration in sludge is 6% by weight and the specific gravity of sludge is 1.02 kg/L [6].

Accounting for 6% solids by weight:

$$SS_{wet\ mass} = 360 \frac{kg}{day} * \left(\frac{100}{6}\right) \% = 6000 \frac{kg}{day} \quad (5\text{-}4)$$

That gives the sludge flow of

$$Q_{sludge} = \frac{6000 \frac{kg}{day}}{1.02 \frac{kg}{L}} = 5882.35 \frac{L}{day} \quad (5\text{-}5)$$

Eq. 5-5 is converted to lb/day, density of sludge is 8.5 lb/gal [16].

$$5882.35 \frac{L}{day} * \frac{1gal}{3.785L} * 8.5 \frac{lb}{gal} = 13210 \frac{lb}{day} * \frac{0{,}453kg}{1lb} = 5984.13 \frac{kg}{day} \quad (5\text{-}6)$$

5.6.2 Heat Requirements of Digesters

The heat required for sludge is determined using Eq. 4-9.

$$13210 \frac{lb}{day} * (90 - 60)°F * 1 \frac{Btu}{lb} °F = 396301 \frac{Btu}{day} = 418 \frac{MJ}{day} \quad (5\text{-}7)$$

A single typical size digester is considered and the heat loss from the digester tank computed in Appendix A was 1543 MJ/day.

The total heat required for the digesters = the heat loss from digester tanks and the heat required for sludge.

That gives:

$$(1543 + 418) \frac{MJ}{day} = 1961 \frac{MJ}{day} \quad (5\text{-}8)$$

5.6.3 Heat Recovery from Fuel Cell

The heat recovery from the FC is determined by multiplying heat output of the FC by its operating hours a day. The FC´s heat output is 2004.6 MJ/hr. (from Table 3.3) and it will be operating approximately 3.5 hours a day according to the system simulation. Eq. 5-9 provides the heat recovery from the FC per day.

$$2004.6\,\frac{MJ}{hr} * 3.5\,\frac{hr}{day} = 6925\,\frac{MJ}{day} \qquad (5\text{-}9)$$

The heat recovered from the FC technically covers the thermal energy required for the digesters which is 1961 MJ/day.

5.7 Results and Discussion

The system simulation and optimization results suggest that the combination of PV - FC is cheaper alternative than WT - FC and PV - WT - FC combined unit. Nevertheless, it is not economically viable to apply the HRES unit, as the cost to generate electricity is way beyond the current tariff. As it can be observed from Table 5.2, it costs 1.14 $/kWh to generate electricity, compared to the current rate, 0.12 $/kWh. There are number of features affecting the result, the insufficient amount of CH_4 produced on site, the high cost of FC unit and the current electricity charge rate is the lowest in Europe[22]. However, the economically most feasible hybrid system is PV - WT - Diesel generator. This unit combination has the potential of reducing the cost of electricity to 0.41 $/kWh. However, it is still not a viable alternative, the objective of this study is to eliminate the use of energy from fossil fuel.

Table 5.2 Hveragerði WWTP - The overall HRES unit summary

	HRES unit
Flow at the WWTP (m^3/day)	**2400**
Heat requirement for sludge (MJ/day)	**418**
Heat loss from digesters (MJ/day)	**1,543**
Heat potential from FC (MJ/day)	**6,925**
Total digester heat requirement (MJ/day)	**1,961**
% of heat used for digester heat load	**28**
CH_4 produced on site (m^3/year)	**49,275**
CH_4 used for electricity generation (m^3/year)	**47,382**
Cost of electricity present ($/kWh)	**0.12**
Cost of electricity with HRES Unit ($/kWh)	**1.14**

[22] www.energyusecalculator.com/global_electricity_prices.htm

The system is considered with a project lifetime of 25 years and with an annual real interest rate of 5%[23]. The project NPC is $2,406,470, the capital investment cost for the system is $2,271,330. The component replacement cost is estimated at $271,379 and the maintenance and operation cost at $205,356. Also, $341,595 can be salvaged at end of project life time. The operating cost of the system is $9,589 a year. Compared to the current tariff the WWTP is on, $0.12, the optimized system levelized cost of energy is $1.14 kWh. Table 5.3 provides the overall cost breakdown. The cost of components that are present in the WWTP such as, heat exchangers and digesters are not evaluated. The results from HOMER simulation can be seen in Appendix F.

Table 5.3 Hveragerði WWTP - The HRES unit cost breakdown summary

Component	*Capital ($)*	*Replacement ($)*	*O&M ($)*	*Fuel ($)*	*Salvage ($)*	*Total ($)*
PV	267,330	0	18,745	0	-19,138	266,937
Fuel Cell	1,674,000	0	186,611	0	-234,604	1,626,007
Batteries	300,000	260,072	0	0	-81,208	478,863
Converter	30,000	11,307	0	0	-6,644	34,662
System	**2,271,330**	**271,379**	**205,356**	**0**	**-341,595**	**2,406,470**

Fig. 5.6 presents the cash flow summary of the system components by NPC. FC has the highest cash flow share over project lifetime with 67% followed by batteries with 19%.

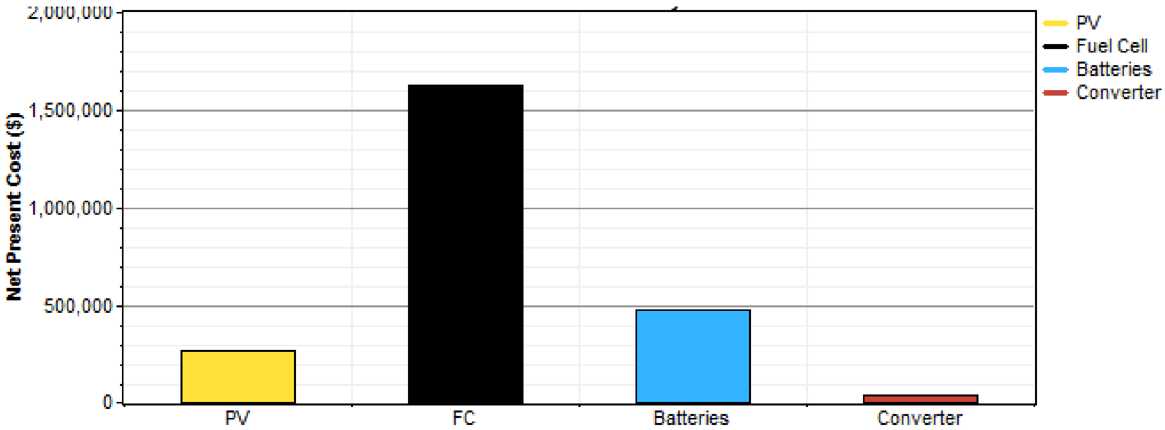

Figure 5.6 Hveragerði WWTP - The cash flow summary

[23] www.datamarket.com/data/set/1497/real-interest-rate#!ds=1497!gad=3k.y.v.1r.4g.2n&display=line.

6 Summary and Conclusions

The study presents the economic assessment and unit configuration for a hybrid renewable energy system designed to serve a WWTP. The HRES unit assessment is performed for plants serving a population of 80,000 and 2300. Electricity consumption data of Kailua and Hveragerði WWTP was used as a case study. The objectives of this paper were, to utilize wind- and solar energy and the useful end product resulted from anaerobic digestion process, such as methane, for cogeneration (CHP) purpose at the site. The system units included FC, WT and PV, and economical and technical evaluations were conducted. The cost of project and the system unit lifecycle costs and sizes were estimated. The study showed that renewable energy sources can fully and safely power the facilities and the power generation share by components is compared in Fig 6.1.

The excess power generated by HRES in Kailua plant, was 24.6% of the annual power generation. In order to utilize this excess electricity, some alternatives need to be considered such as, grid feed-in. The system simulation showed that for the HRES system, it is not a feasible option to store the excess electricity for later use, since the capture and store is typically an expensive operation. The result suggested that it is economically viable to utilize methane produced on site for Kailua WWTP.

For Hveragerði, there were limitations for CHP application, like low potential of methane on site and high cost of FC unit. Generally, CHP applications have been thought to be feasible only at facilities with flow rate higher than 37,000 m^3/day [19].

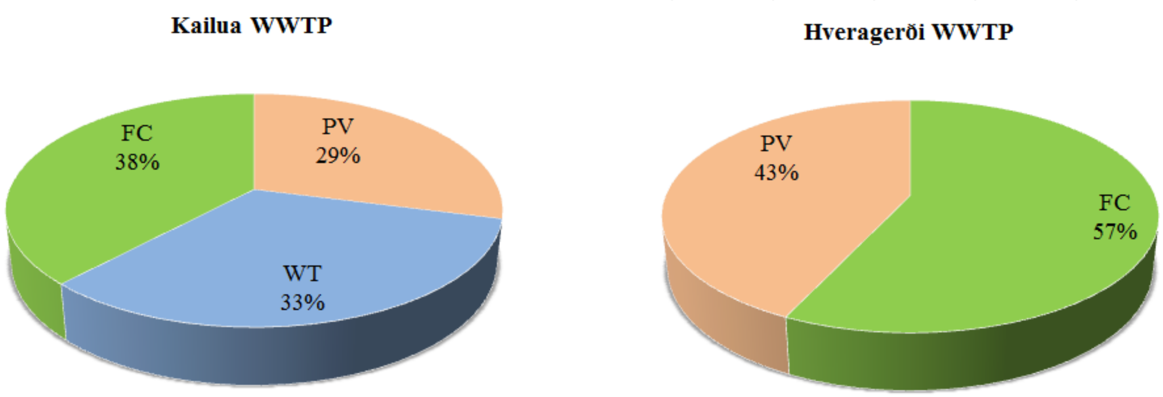

Figure 6.1 The power generation share of components

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Appendix A

In this section the heat loss from the digester tank was estimated[24].

Typically sized digester was used in this calculation. It was assumed that the specific heat of sludge is the same as water. The heat loss was calculated with the following equation.

$$q = UA * \Delta T$$

Where q is the heat loss (Btu/h), U is the overall coefficient of heat transfer (Btu/ft^2*h*°F), A is the cross-sectional area through which the heat loss is occurring, ft^2 and ΔT is the temperature difference between the incoming sludge and the sludge contents in digester. The U values are retrieved from Table 14 in Appendix C. The following conditions are applied

- The temperature of the sludge contents in digester, 90 °F (32 °C), from s. 4.6.2
- The annual average temperature in Honolulu, HI, 73 °F (22.7 °C)[25].
- Earth next to wall, 32 °F (0 °C)
- Earth below floor, 42 °F (5 °C)

The cylindrical digester tank sizes

- Diameter: 60 ft. (18m)
- Side depth: 25 ft. (7.6 m)
- Center depth: 30 ft. (9m)

Area of the tank:

$$Floor\ area = \pi * 30^2 = 2827 ft^2$$

$$Wall\ area = \pi * 60 * 25 = 4712 ft^2$$

$$Roof\ area = \pi * 30(30^2 + 5^2)^{1/2} = 2866 ft^2$$

Heat loss:

$$q_{floor} = 0.15 \frac{Btu}{ft^2} * °F * h * 2827 ft^2 * (90 - 42°F) = 20354 \frac{Btu}{h}$$

$$20354 \frac{Btu}{h} * 24 = 488506 \frac{Btu}{day}$$

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[24] I. Metcalf & Eddy, Wastewater Engineering, Treatment, Disposal and Reuse, McGraw-Hill Inc, 1991.

[25] www.usa.com/honolulu-hi-weather.htm

$$q_{wall} = 0.12 \frac{Btu}{ft^2} * °F * h * 4712 ft^2 * (90 - 32°F) = 32795 \frac{Btu}{h}$$

$$32795 \frac{Btu}{h} * 24 = 787092 \frac{Btu}{day}$$

$$q_{roof} = 0.16 \frac{Btu}{ft^2} * °F * h * 2866 ft^2 * (90 - 73°F) = 7795 \frac{Btu}{h}$$

$$7795 \frac{Btu}{h} * 24 = 187092 \frac{Btu}{day}$$

The total heat loss for single tank:

$$q_{total} = (488506 + 787092 + 187092) \frac{Btu}{day} = 1462689 \frac{Btu}{day}$$

$$1462689 \frac{Btu}{day} = 1543 \frac{MJ}{day}$$

The total heat loss for Kailua WWTP:

$$1543 \frac{MJ}{day} * 4_{number\ of\ tanks} = 6172 \frac{MJ}{day}$$

Appendix B

Table 6.1 Composition of medium strength untreated domestic wastewater[26]

Constituent	*Concentration, mg/L*
Bacteria	10^7-2 x10^8
Total solids	450
Total volatile solids	300
Suspended solids	250
Volatile suspended solids	200
Total dissolved solids	200
BOD_5	150-250
Nitrate and nitrite nitrogen as N	<0.6
Organic nitrogen as N	25-85
Ammonia nitrogen as N	15-50
Total phosphorus	6-12
Soluble phosphorus	4-6

[26] R. L. Droste, Theory and Practice of Water and Wastewater Treatment, John Wiley & Sons, Inc., 1997.

Appendix C

Table 6.2 Typical values for the overall coefficients of heat transfer for calculating digester heat loss[27]

Item	*Btu/ft2*°F*h*
Plain concrete walls (above ground)	
12 in thick, not insulated	0.83-0.90
12 in thick with air space plus brick facing	0.32-0.42
12 in thick wall with insulation	0.11-0.14
Plain concrete walls (below ground)	
Surrounded by dry earth	0.10-0.12
Surrounded by moist earth	0.19-0.25
Plain concrete floors	
12 in thick, in contact with moist earth	0.10-0.12
12 in thick, in contact with dry earth	0.05-0.07
Floating covers	
With 1,5 in wood deck, built-up roofing, and no insulation	0.32-0.35
With 1 in insulating board installed under roofing	0.16-0.18
Fixed concrete covers	
4 in thick and covered with built-up roofing, not insulated	0.70-0.88
4 in thick and covered, but insulated with 1 in insulating board	0.21-0.28
9 in thick, not insulated	0.53-0.63
Fixed steel cover (1/4 in thick)	0.70-0.90

[27] I. Metcalf & Eddy, Wastewater Engineering, Treatment, Disposal and Reuse, McGraw-Hill Inc, 1991.

Appendix D

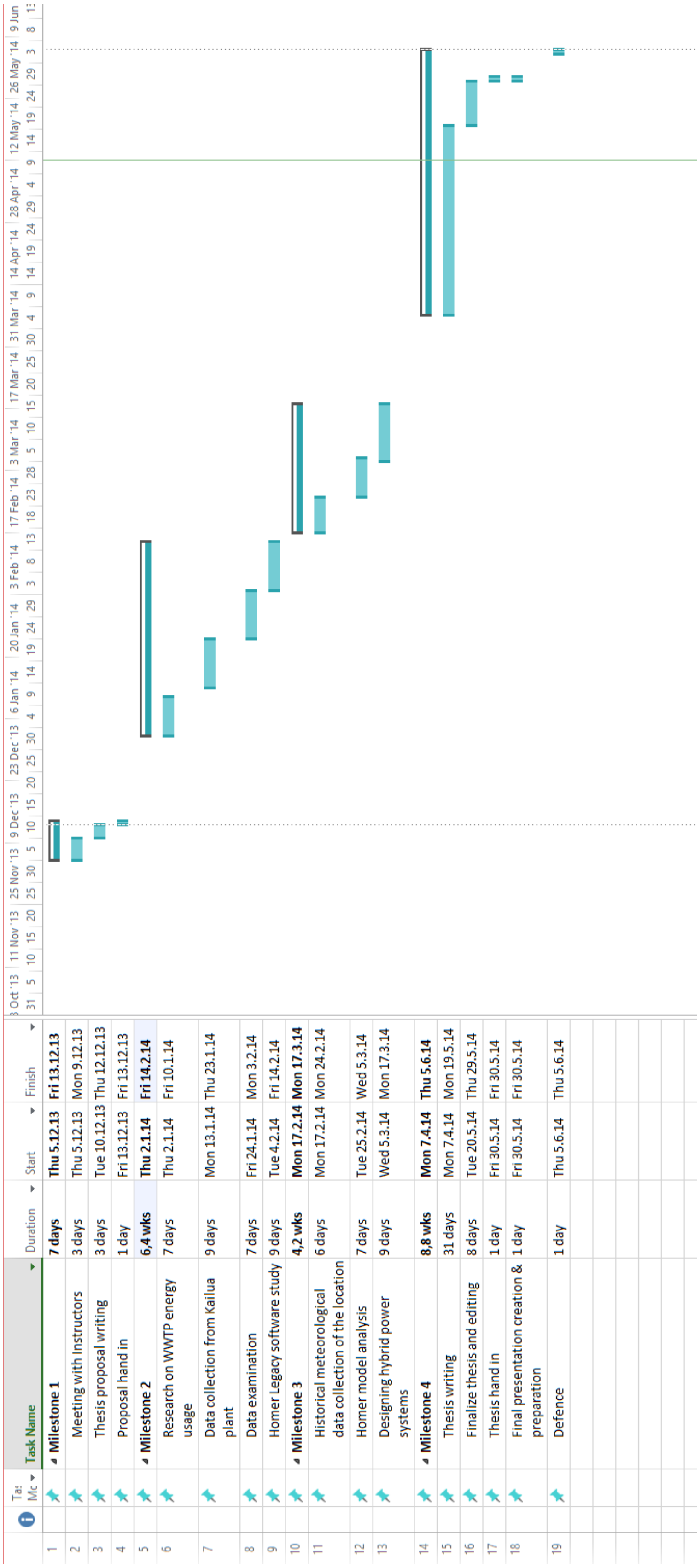


Figure 6.2 Project schedule in Gnatt chart

Appendix E

PV (kW)	WT	FC (kW)	Batteries	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Methane (m3)	FC (hrs)	Batt. Lf. (yr)
1500	10	1200	1500	1500	$ 17,244,500	510,965	$ 28,497,568	0.173	0.62	918,445	3,993	10.4
	17	1200	2750	1400	$ 17,482,300	564,998	$ 29,925,328	0.182	0.57	934,211	3,684	12.0

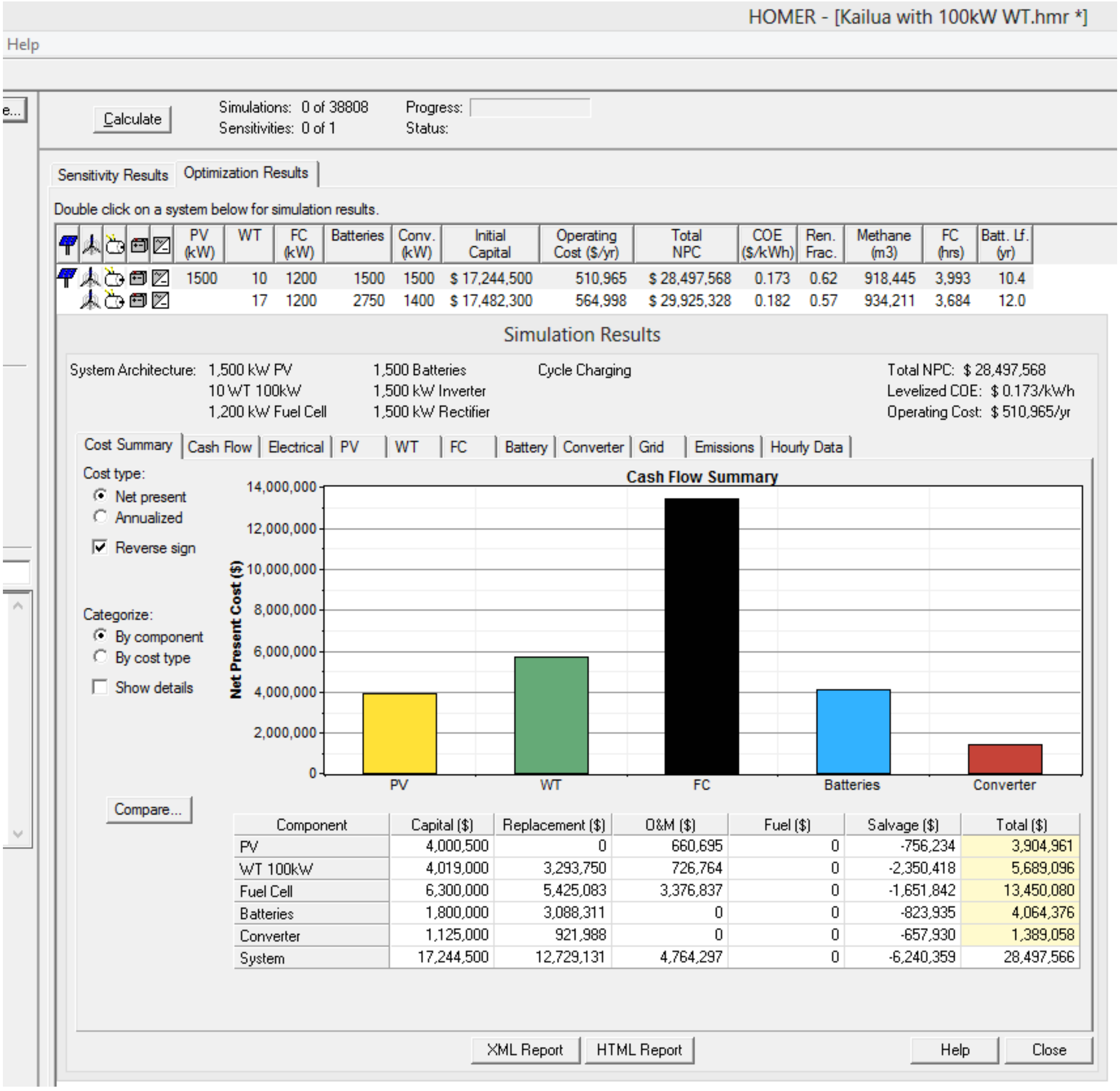
Production	kWh/yr	%
PV array	2,710,003	29
Wind turbines	3,048,186	33
Fuel Cell	3,567,447	38
Total	9,325,636	100

Consumption	kWh/yr	%
AC primary load	7,481,261	100
Total	7,481,261	100

Quantity	kWh/yr	%
Excess electricity	1,079,551	11.6
Unmet electric load	130	0.0
Capacity shortage	2,298	0.0

Quantity	Value
Renewable fraction	0.617

Figure 6.3 Kailua WWTP - Simulation results in HOMER (Electricity production)



PV (kW)	WT	FC (kW)	Batteries	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Methane (m3)	FC (hrs)	Batt. Lf. (yr)
1500	10	1200	1500	1500	$ 17,244,500	510,965	$ 28,497,568	0.173	0.62	918,445	3,993	10.4
	17	1200	2750	1400	$ 17,482,300	564,998	$ 29,925,328	0.182	0.57	934,211	3,684	12.0

Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	4,000,500	0	660,695	0	-756,234	3,904,961
WT 100kW	4,019,000	3,293,750	726,764	0	-2,350,418	5,689,096
Fuel Cell	6,300,000	5,425,083	3,376,837	0	-1,651,842	13,450,080
Batteries	1,800,000	3,088,311	0	0	-823,935	4,064,376
Converter	1,125,000	921,988	0	0	-657,930	1,389,058
System	17,244,500	12,729,131	4,764,297	0	-6,240,359	28,497,566

Figure 6.4 Kailua WWTP - Simulation results in HOMER (Cash flow summary)

Appendix F

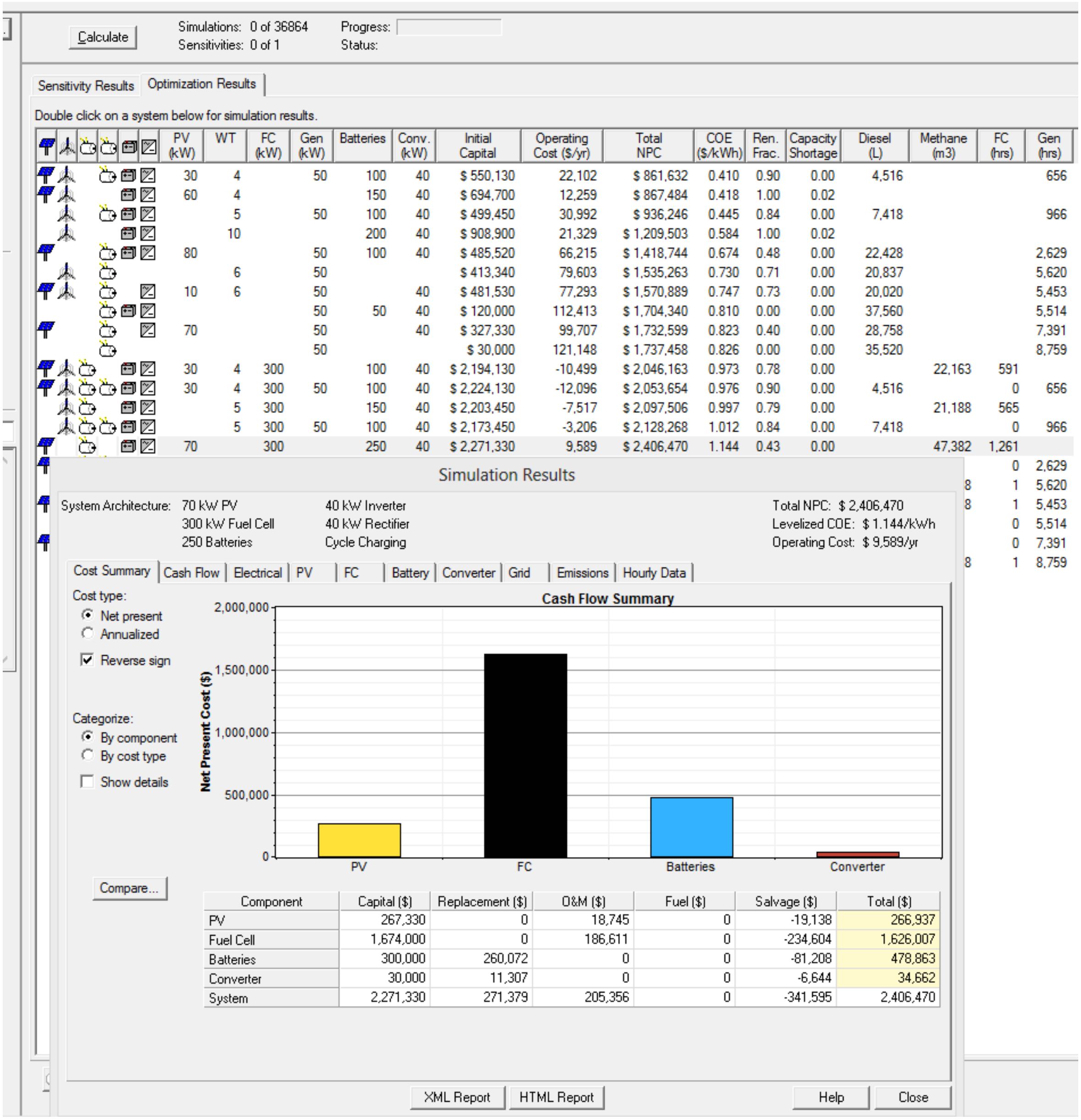


Figure 6.5 Hveragerði WWTP - Simulation results in HOMER (Cash flow summary)