Cape Peninsula
University of Technology

AN ANALYSIS OF DYNAMIC MODELLING OF RENEWABLE ENERGY SOURCES FOR WASTEWATER PUMPING STATIONS IN CAPE TOWN

by

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DECLARATION

I, Jon-Patrick George Pillay, declare that the contents of this dissertation represent my own unaided work, and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

	23 May 2023
Signed	**Date**

Abstract

This dissertation studies renewable energy sources of solar photovoltaic and wind turbines systems to attain self-sustainability for wastewater pumping within the wastewater treatment process as a potential green replacement to that of electric or diesel power systems currently in our city environment today. The data of wastewater pumping stations in Cape Town, South Africa are presented as case studies. In recent years, Cape Town has also encountered a severe drought lasting from 2015 until 2018. South Africa has for several decades experienced rolling blackouts as a result of total dependency on grid energy, with Cape Town not being exempted, placing a serious focus on these two critical resources, namely water and energy.

There is consensus that the treatment of wastewater is estimated to account for 1% of the energy consumption of national grids around the world, however very few countries have undertaken this kind of study. It is also estimated that wastewater pumping accounts for 12 – 19% of the total energy expenditure within the treatment process. This dissertation looks to establish a benchmark for the energy intensity (kWh/m³) wastewater pumping stations in Cape Town by collating the daily energy consumption against effluent pumped and comparing this to other countries. This dissertation also analyses the dynamic modelling of renewable energy sources towards the application and feasibility of pumping at wastewater pumping stations located across Cape Town. Hybrid Optimisation of Multiple Energy Resources (HOMER) issued to carry out simulations based on the historic energy load profiles of these wastewater pumping stations.

The results indicate that Cape Town has an average specific wastewater pumping energy intensity of 0.25 kWh/m³, furthermore, that wind and solar energy, as simulated, present viable opportunities for energy supplies of wastewater pumping station in Cape Town. The results could further imply that such technologies are implemented in the foreseeable future.

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Abbreviations and acronyms

AMR	Automated meter reader
CCT	City of Cape Town
CHP	Combined heat pump
COE	Cost of energy
COD	Chemical oxygen demand
CO_2	Carbon dioxide
CSV	Comma-separated values
ECCD	Energy and Climate Change Directorate
EGD	Electricity Generation and Distribution
GHG	Greenhouse gas
HOMER	Hybrid Optimization Model of Electric Renewables
IDP	Integrated Development Plan
KPI	Key performance index
MDUS	Meter data unification system
MOE	Ministry of Environment
N	Nitrogen
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
PE	Population equivalent
PS	Pumping station
RE	Renewable energy
RES	Renewable energy system
SD	Secure digital

AMR	Automated meter reader
SECR	State of Energy and Carbon Report
SEMD	Sustainable Energy Markets Department
SER	State of Energy Report
SFD	Smart Facility Dash
SIM	Subscriber identity module
SQL	Standard query language
tCO2e	tonnes of carbon dioxide equivalent
TPU	Total power usage
TRV	Total replacement value
TSS	Total suspended solids
UGDM	Universal Graphic Data Manager
USB	Universal series bus
USA	United States of America
WSD	Water and Sanitation Directorate
WT	Wind turbines
WSIR	Water Sector Input Report
WWE	Wastewater effluent
WWI	Wastewater influent
WWT	Wastewater treatment
WWTP	Wastewater treatment plant
WWP	Wastewater pumping
WWPS	Wastewater pump station
WWRP	Wastewater reclamation plant

Constants

Symbol	**Meaning (units)**
hr	Hour
kg	Kilogram
km	Kilometre
m	Meter
m^3	Meter cubed
msec	Milliseconds
Ml	Mega-litre
W	Watt
kW	Kilowatt
kWh	Kilowatt-hour
TWh	Terawatt-hour
GWh	Gigawatt-hour
Q	Flow (m^3/day)

Publications related to this Dissertation

Pillay, JG, Exploring the feasibility of solar inverters using mathematical modelling for wastewater pumping at Wood Drive Sewage Pump Station, Parklands, Cape Town (November 25, 2020). AIUE Proceedings of the 18th Industrial and Commercial Use of Energy Conference 2020 ELECTRONIC COPY AVAILABLE AT: https://ssrn.com/

Other publications during this study period

Simphe, EK and Pillay, JG and Ndihokubwayo, R and Nalumu, DR, Best practices for improving HVAC systems energy efficiency in buildings (July 3, 2021). International Journal of Building Pathology and Adaption ELECTRONIC COPY AVAILABLE AT: https://www.emerald.com/insight/2398-4708.htm

CHAPTER 1: INTRODUCTION

1.1 Introduction to dissertation

Wastewater pumping stations (WWPS) are an integral part of the wastewater treatment (WWT) process referred to as the pumping/collection stage and/or primary treatment stage. Before the process of WWT begins, the wastewater effluent (WWE) is conveyed from its origin (households and industries) to the wastewater treatment plant (WWTP), a process that is not usually gravity determined (Smith et al., 2018). A WWPS is normally located a fair distance away from the WWTP and is connected via a series of pipes called 'rising-mains'. The WWPS operates as a stand-alone operating system, with its own electrical feed, that conveys wastewater influent (WWI) to the WWTP.

A standard WWPS is designed according to what flows (m^3/time) into the facility and the amount of head (m) that the pump(s) should overcome. In addition, WWPSs are also designed with the following in mind, namely: 1) the peak wet weather flow; 2) pipe infiltration; 3) the population/area it serves; 5) future population growth and 6) the total energy losses in the pipeline (Hillman, 1980). Approximately 20% of the world's energy consumption stems from the use of pumping systems (Davidson, Benson and Drive, 2003). Figure 1 below is a typical cross-section of a WWPS in Eindhoven, Netherlands.

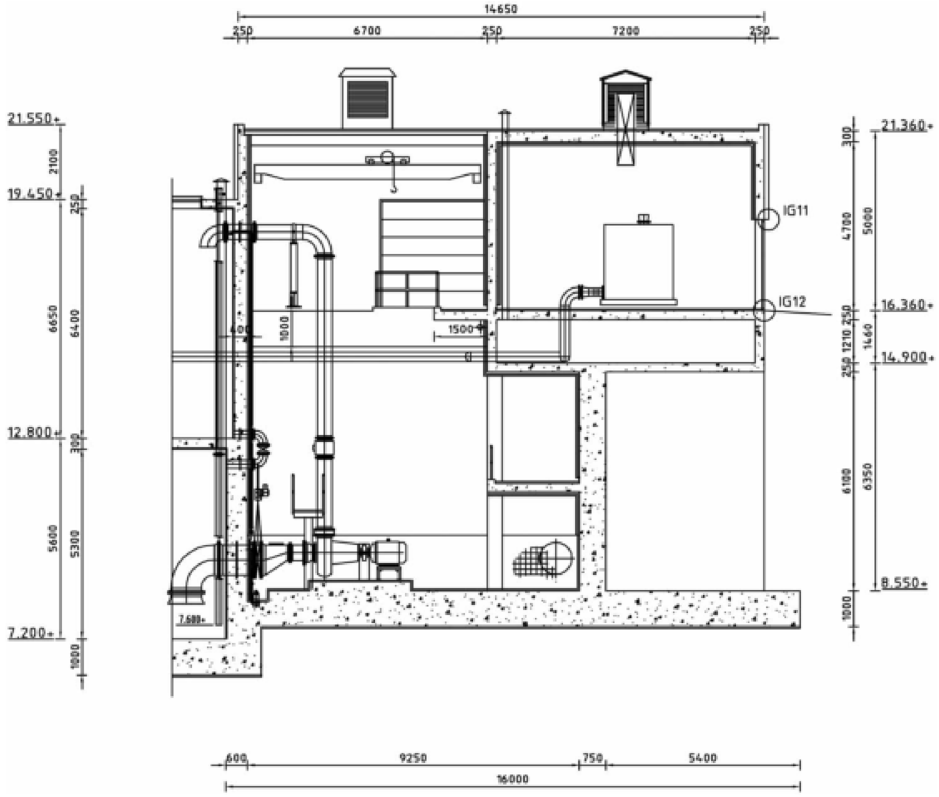


Figure 1: Typical cross-section of a WWPS in Eindhoven, Netherlands (De Keyser *et al.*, 2014)

Factors like topography, pipe infiltration, age of the pumping station, types of pumps, technology used and also plant maintenance etc. all play a vital role in the energy efficiency of WWTPs and WWPSs, as these conditions differ worldwide (Gu *et al.*, 2017; Xu *et al.*, 2017). However, it is the design, construction, maintenance and input energy costs is what makes these facilities costly (Davidson, Benson and Drive, 2003; Longo *et al.*, 2016). Davidson, Benson and Drive, (2003) stated that pumping stations could be viewed as significant operational facilities within the municipality because of their health, safety and environmental impacts they have within the built environment. Greenhouse gas (GHG) emissions and climate change has increased the status of renewable energy, and the exploitation of renewable energy (RE) resources is viewed as sustainable (Helal, Ghoneim and Halaby, 2013). Solar photovoltaic (SPV) has been around since the 1970's and is an ideal energy substitute to the conventionally based pumping systems of diesel and electricity (Li *et al.*, 2017). Windmills have been a mechanical source of energy for grinning seeds and pumping for water thousands of years, however modern technology has enabled this form of energy converted into electricity. Furthermore, South Africa has a strong wind resource potential along it's coast with the provinces of the Western Cape and Eastern Cape displaying the most promise (*Department of Mineral Resources and Energy*, 2022). Bofinger *et al.*, (2016) found that the REs found in South Africa was considered to be 'world-class' for the introduction of large-scale renewable energy systems (RESs) into the electricity grid. Modern technology has improved the methods of cost effective production, improved efficiency and also performance of solar cells, with the future of this industry only expected to improve (Duffie, Beckman and McGowan, 1985). The same can be mentioned regarding wind turbine systems, where the power ratings of new wind technologies has increased and capital outlay decreased (Helal, Ghoneim and Halaby, 2013).

Research has shown that local governments and municipalities were expending 12 – 30% of the electrical energy consumption on WWT (Miller, Ramaswami and Ranjan, 2013; Panepinto *et al.*, 2016; Wang *et al.*, 2016). Walther, (2013) concluded that aeration and pumping were the biggest energy consumers within WWT at 60% and 12% respectively. Others had concluded that aeration accounted for as much as 78% (Daw *et al.*, 2012) and pumping 30% (Brandt *et al.*, 2011) of the total energy requirements during the WWT process.

The motivation behind this research would be to look at ways to enable WWPSs to be more efficient with SPV and wind turbines (WT) as an alternative input energy or RE source.

1.2 Background to the research problem

Increasing water scarcity has amplified the world's urban water cycles dependency on energy for water delivery and treatment. Energy access can be an obstacle to urban cities resulting in both energy and water shortages, along with increased levels of water pollution (Singh, Carliell-Marquet and Kansal, 2012). A collective sustainable development principal has seen the world place an emphasis on climate change, energy efficiency and carbon-friendly energy substitution (Friedrich, Pillay and Buckley, 2009). South Africa is a country which is prone to water scarcity and an extreme emphasis has been placed on its water resources, particularly within the Western Cape Province, and also other parts of the country, over the last decade (Knight, 2019). It's water scarcity was aggravated by a drought lasting from 2015 until 2018 resulted in severe water restrictions in many parts of the country, and the consequences of this has had a serious knock-on effect on the economy (Conradie, 2020). Concurrently, the drought, proliferated with intensive load shedding throughout the country, has placed a sombre focus on these two crucial resources, both essential for the healthy population growth and economic development of South Africa (Hallowes, 2019). Sewage overspills has disastrous consequences for a cities infrastructure. Furthermore, the major cities of Ekurhuleni, Tshwane, Johannesburg and Cape Town are all at risk of sewage overflows, due to inactive WWPSs, as a result of load shedding in South Africa (de Villiers, 2019). The economic impacts of South Africa's chronic water shortages and poor water planning cannot be underestimated (Blignaut and Van Heerden, 2009).

The inclination of planners and engineers spanning the globe currently recognises that water-planning and energy-planning runs parallel and concurrently with one another, a concept known as the 'water-energy nexus' (Hardy, Garrido and Juana, 2012). Capodaglio, Ghilardi and Boguniewicz-Zablocka, (2016) have found that years of static engineering practices within the urban water management cycle are receiving new industrial and technological approaches, and I am in agreement with both these statements.

1.3 Statement of research problem

The technology of solar water pumping has traditionally been used for the application towards irrigation of farmlands and also rural water supply as it is relatively cost effective with zero fuel consumption and minimal maintenance requirements (Chandel, Nagaraju Naik and Chandel, 2015). The application of WT within the water-energy-nexus has largely been ignored, although this resources can have a meaningful contribution within the water management cycle (Li *et al.*, 2012).

One can only assume that the application of RESs such as e.g. solar photovoltaic and wind turbines etc. has not been applied to wastewater pumping, as this could be attributed to the meaningful amounts of energy it would require, as well as the reliability of the resource to provide this type of energy, as it could prove erratic. Another reason for this, is that most engineering professionals were not providing perspicacity into energy efficiency for wastewater infrastructure (Rojas and Zhelev, 2012).

1.4 Research question

What sort of RESs would be able to meet the energy requirements of WWPSs in Cape Town and would it be feasible to invest in such infrastructure as opposed to the dependency of conventional grid power and back-up diesel generators?

1.5 Objectives & Outcomes

The intellectual puzzle driving this study is aimed at exploring the possibilities of RESs to be used for WWPS in a manner that is economically feasible and carbon neutral. In order to achieve this, the following objectives will be met:

- To study the international ranges for energy intensities (kWh/m³) for WWPSs for countries around the world.
- To benchmark a range for energy intensity (kWh/m³) for the WWPSs of Cape Town.
- To explore if RESs can meet the energy requirements completely or partially for the WWPSs in Cape Town.
- To investigate the feasibility of such possible energy interventions was to be implemented in Cape Town WWPSs

From this research a specific energy intensity level comparison, in kWh/m³, will provide ranges both internationally and locally (Cape Town) for pumping wastewater and the expected outcomes will deal specifically with:

- Analysing the specific energy intensity consumption data from WWPS around the globe.
- Analysing the benched marked specific energy intensity consumption data from WWPS in Cape Town.
- Comparing the feasibility of renewable energy options for WWPSs in Cape Town
- Comparing these options in terms of potential energy savings; reduction in carbon emissions and money saved.

1.6 Delineation

This study will focus on recent historic energy consumption patterns at the WWPSs in Cape Town as these will be fed into HOMER, software modelling tool utilized in this study, for analysis. The RESs of SPV and WTs will be investigated as a form of substitution for grid energy. Conduit hydropower and other types of renewable energy sources will not be considered. Energy efficiency strategies will not be analysed or considered. The simulations will not consider any surplus energy being put back into the grid, meaning it will only consider standalone function, with grid and diesel generators as backup. Only 20 of the 406 WWPSs found in Cape Town will be evaluated. Modelling the actual peripheral loading inside these WWPSs will not be a part of the modelling process and focus of study and the designing of any new technology will not be explored. The study will also not consider any currently policies, laws and by-laws present in the South African energy landscape.

1.7 Significance of the research problem

The world's energy consumption used to pump and treat water and wastewater ranges between 2-3%, on average, for industries and the population residing in the urban environment (Venkatesh, Chan and Brattebø, 2014). The United States of America is consuming 4 % of their available energy grid to perform this (Rothausen and Conway, 2011; Wang *et al.*, 2016). Other researchers has indicated that countries all over the globe are expending 0.25 – 1.0 % of their available grid energy to pump and treat wastewater alone, whilst Israel was consuming 10 % of the national energy grid on pumping and treating wastewater due to the water scarcity of that country (Gu *et al.*, 2017). Therefore, research in this direction is becoming an increasing necessity.

1.8 Research methodology

The CCT has 27 WWTPs and 406 pumping stations (both sewer and stormwater) according to the CCT's WWT assets register (Manie and Johnstone, 2017).

A recent development in 2018 has seen all of CCT's WWTPs and several WWPSs migration towards smart electrically monitored facilities with data linked servers, which records their energy consumption. Twenty (20) WWPSs was identified as potential case studies because it had primary data records, pertaining to energy consumption dating back to June 2018, with a certain high level of accuracy.

The WWP energy benchmarking will consist of the sampling of flow and energy data for one WWPS which representative about 0.25% found in the Cape Town. Furthermore, flow data will be obtained via the CCT Water and Sanitation Department (WSD) on the sewage flow patterns for the WWPS. Unfortunately, this data will have to be collected on site, as this data is not linked to any server and or cloud and the energy intensity levels extracted manually via Microsoft Excel. From the literature gathered and reviewed, it will later be shown there is not a considerable difference in WWP energy intensity levels found around the globe. Therefore, it would be expected that if a study greater than 0.25% were conducted, it would become an expensive exercise without much added value. However, Jonasson, (2007) demonstrated in his case study of energy benchmarking WWTPs in Austria and Sweden that energy benchmarking plays a crucial role in a WWTPs energy saving and efficiency strategies.

The sampling and collection of energy data of 20 WWPSs is representative of just under 5% found in CCT across the city metropole. The data of these twenty will be grouped and 'binned' statistically where the largest of the energy consumption of each of these bins will be mathematically modelled. The number of models run will depend on the statistical binned groupings. Mathematical modelling software in the form of HOMER will be used to analyse the input data such as e.g. solar irradiance of the area etc. and also the energy produced by the renewable system(s) where these options will be reviewed to match the energy requirements of these facilities.

It is my opinion that this amount of data will suffice for an accurate indication for energy benchmarking of these facilities, and I believe that a study of this nature is in-line with the master's degree in engineering (energy) course requirements.

1.8.1 Data

The data critical to this study is listed as follows below:

- Electrical energy consumption of twenty of CCT's WWPS (kWh/day)

- Wastewater flows into the WWPS (m^3/day)

1.8.2 Research instruments and equipment

HOMER will be used for the mathematical modelling software to simulate and match the inputs of the renewable energy generation and to perform the costing analysis. The existing flow meters and data recorders will be used for the recording of the wastewater flowing into the WWPSs and electrical smart meters will measure the electrical consumption data captured digitally.

1.8.3 Analysis / presentation of results

The extraction of flow and energy consumption data for the CCT WWPS is planned and the following relationships will be established, namely:

- Daily influent wastewater (Q vs time)
- Daily energy consumption (kWh vs time)
- Daily specific energy consumption (kWh/day vs m^3/day)
- HOMER modelling software will be used to design the renewable energy outputs and simulate the feasibility and carbon emission savings.

1.9 Organisation of dissertation

Chapter 1 – Introduction

This chapter gives a background to WWP and the research problem faced. A summary of the objectives and outcomes, problem significance, delineation, research methodology and anticipated outcomes forms this chapter.

Chapter 2 – Literature review

This chapter will begin with Section A introducing the main concepts, namely: water and energy interaction (water-energy nexus), the necessity of WWT and WWTPs design. Section B then moves on to detailing the global landscape of wastewater energy consumption and sectoral energy demand in wastewater. Section C describes the concepts of wastewater energy efficiency and energy recovery towards net-zero carbon emissions and also the concepts of net-zero WWTPs. Section D details global indicators in WWT energy consumption and energy intensities of WWT and WWPs in order to gauge the problem.

Chapter 3 – Theoretical consideration

Section E details case studies of utilizing test method formulas towards energy benchmarking within the WWT framework. Section F details case studies where modelling software was utilized in a WWT scenarios. Both these sections were explored in order to justify the reasoning for proceeding with the study in the particular direction.

Chapter 4 – Methodology

Part 1 of this chapter details data sampling methods, resources and equipment, research design and data collection. Part 2 of this chapter details the use of mathematical software in simulating RES for WWPSs.

Chapter 5 – Results and discussion

The outcome of the energy benchmarking and PSs modelling results is shown and discussed in this chapter. The significance of the results will be addressed in this discussion.

Chapter 6 – Conclusions and Recommendations

Conclusions and recommendations for further research will be made in this chapter.

CHAPTER 2: LITERATURE REVIEW

SECTION A: WATER-ENERGY-NEXUS

2.1 Water and energy interaction

The outdated perception of energy and water has been considered to be that of two independent resources, however their dependence has now been globally recognised (Hardy, Garrido and Juana, 2012). Expanding population growth, climate change and increased pressures on our resources are inhibiting sustainable development as a result of industrial, commercial, public and agricultural sectors (UNESCO, 2012). Smith *et al.*, (2018) stated that several studies have detailed the impacts of climate change on the world's water resources, but few have researched the water sectors usage's fossil fuel carbon footprint. Perrone, Murphy and Hornberger, (2011) stated that research into the water-energy-nexus is gaining attention from the academic community as it is yielding opportunities in the area sustainable development.

2.1.1 Water use in the energy sector

Hightower and Pierce, (2008) stated that the energy sector consumed the second largest amount of water in the world. The 2010 figure for the energy sector's usage was set to be around 583 billion m^3 of water, or 15% of the worlds water consumption (International Energy Agency, 2012). The energy supply chain utilises water in several different ways, which included but is not limited to: 1) power generation, 2) extraction, 3) transportation and 4) fossil fuel processing (Jordaan *et al.*, 2013). Furthermore, power generation consumes large amounts of water for thermal processes and cooling (Macknick *et al.*, 2012). However, the studies of water usage in energy production was shown to be receiving more attention in water-scarce countries (Mittal, 2010).

2.1.2 Energy usage in water sector

Water-resource management entities consider water-related energy as either direct energy or indirect energy. Energy consumption within the water cycle is dependent on various factors with can included, but is not limited to: 1) climate; 2) average rainfall; 3) seasonal temperature; 5) total water requirement; 6) volume of water and 7) technology utilized (Kenway *et al.*, 2011). The consumption of energy within the water sector has increased substantially, where in the United Kingdom (UK) this is estimated to be 3% of the national supply (Smith *et al.*, 2018).

SECTION B: WASTEWATER ENERGY LANDSCAPE

2.2 Necessity of wastewater treatment

Our environments natural ability to deal with human excreta has been overwhelmed by excessive change to natural surroundings and global growing human populations (Hillman, 1980). Human excreta is hazardous for humans encountering it, as it can be a carrier for harmful and/or deadly parasites, viruses, bacteria and fungi. In order to deal with this problem safely, engineers designed their cities to convey the excreta via means of subterranean pipe networks. In order for the system to work, water added to the excreta enables this matter to flow, which results in a term that we commonly understand as ‘sewage’. The sewage, in most cases, is transported by means of gravitational flow to a WWTP (Smith *et al.*, 2018), however a WWPS is incorporated into the networks design where gravitation is not possible (Hillman, 1980). WWTPs are the cornerstone of energy-water interfaces (Xu *et al.*, 2017). This process consumes energy in order to remove pollutants from the environment (Gu *et al.*, 2017). Over several decades, the standards of wastewater treatment WWT have increased significantly, bringing with it more sophisticated and energy intensive technologies (Jenicek *et al.*, 2013). In most cases energy, in the form of the electrical grid, dispenses power to the WWTP, stems from fossil fuel combustion (Longo *et al.*, 2016).

2.3 Global wastewater treatment plant design

Most WWTPs throughout the world were designed to attain certain effluent standards without an adequate forethought of energy efficiency requirements and that improvement in this area was possible (Rojas and Zhelev, 2012). Ashrafi, Yerushalmi and Haghighat, (2014) concluded that WWTPs energy consumption and corresponding greenhouse gas (GHG) emissions were a cause for global concern. Friedrich, Pillay and Buckley, (2009) stated that a common pursuit of attaining global sustainable development with regards to climate change, conservation of energy and energy efficiency was gaining an increased attention. WWT energy consumption has received international awareness not only because of its demand for sizable on-site energy e.g. electricity, used for aeration and pumping, but also for the large amounts of chemicals used during the treatment process. However, electricity is the main source of energy associated with the major stages of treatment for wastewater, e.g. pumping; mixing; separation and activated sludge treatment etc. but is not limited to the use of natural gas and also fossil fuels (Longo *et al.*, 2016). Olsson, (2012) stated that the water-energy nexus has become of significance importance in recent times due to it being a long neglected subject within the urban water management cycle. Capodaglio and

Olsson, (2020) stated that new approaches and strategies was beginning to replace years of fixed and outdated practices within the urban water cycle.

2.4 Global wastewater treatment's energy consumption

Research trends have indicated that energy consumption in WWT has yet to be established at an international level and reasons for the differences in energy consumption between the few countries, where this is known, are still being debated (Wang *et al.*, 2016). The differences in percentages across the various nationalities energy consumption patterns and energy intensities in WWT are mainly affected by these countries stances on effluent quality standards, budget constraints and policy implementation (Gu *et al.*, 2017). It is estimated that between 1 – 18% of urban electrical energy is used to transport and treat both water and WW (Olsson, 2012). Smith *et al.*, (2018) reviewed China's urban water and wastewater systems energy dependency and found that this represented one of the primary costs as well as a foremost contributor GHG emission. Another finding was that China's cities' WWT had tripled from 2007 (17.0 x 10^9 m^3) to 2015 (46.7 x 10^9 m^3) which resulted in an energy consumption of 3.90 TWh in 2007 compared to 14.0 TWh in 2015. However, others are stating that this figure is closer to 100TWh/year (Rothausen and Conway, 2011; Wang *et al.*, 2016; Yan *et al.*, 2016). The national grid energy consumption of various countries corresponding with WWT is represented in Table 1 below:

Table 1: Annual energy consumption and percentage of grid consumption associated with wastewater treatment across different countries

Countries/ Region	**WWT energy Consumption (TWh/year)**	**Consumption of grid energy for WWT (%)**	**Reference**
China	100.00	0.25	(Rothausen and Conway, 2011; Wang *et al.*, 2016; Yan *et al.*, 2016)
Europe	27.00	1.00	(Haslinger, Krampe and Lindtner, 2016; Sun *et al.*, 2019)
Germany	4.40	0.70 – 1.00	(Wang *et al.*, 2016; Maktabifard, Zaborowska and Makinia, 2018)
Israel	-	10.00	(Wang et al., 2016)
Italy	3.25	-	(Campanelli, M., Foladori, P. and Vaccari, 2013)
Korea	-	0.50	(Chae and Kang, 2013)
Poland	5.50	2.50 – 3.50	(Maslon, Wojcik and Chimelowski, 2018)
Sweden	-	1.00	(Gu *et al.*, 2017)
USA	21.00	0.60 – 4.00	(Rothausen and Conway, 2011; Wang *et al.*, 2016; Yan *et al.*, 2016; Xu *et al.*, 2017)

- no present data found

Mo and Zhang, (2013) found that there was more than 15 000 municipal WWTPs in the United States of America (USA) which served approximately 78% of its inhabitants. Wang *et al.*, (2016) estimated that the USA, which has the largest economy in the world, is consuming 0.6% of their national grid supply for the treatment of wastewater, whilst others are stating that this is as much as 4% of the USA's national grid supply (Rothausen and Conway, 2011; Yan *et al.*, 2016; Xu *et al.*, 2017). Rothausen and Conway, (2011) reported that the USA WWT sector accounted for an approximate energy consumption of 21 TWh/year compared to China's 100 TWh/year. Both significant contributors to greenhouse gases (GHG's) as their primary sources of energy was grid energy stemming from fossil fuels. The energy expended on Europe's WWT is estimated to be at 27.0 TWh/year (Sun *et al.*, 2019). For WWT within Europe countries such as e.g. Germany and Sweden are consuming a proportion of 0.7% and 1% of their national grid energy respectively (Haslinger, Krampe and Lindtner, 2016; Gu *et al.*, 2017). Energy consumption within German all municipal water systems (wastewater and water) was estimated to have utilized 2.4 TWh/year in 2007 (Plath, Ernst and Wichmann, 2014), but has now been estimated to have increased to 4.4 TWh/year towards WWT alone, and is also estimated to account for 20% of their municipal energy consumption (Wang et al., 2016). Poland is estimated to be consuming 2.5 – 3.5% of its available grid energy to treat wastewater amounting to 5.5 TWh/year (Maslon, Wojcik and Chimelowski, 2018). The Italian electrical consumption for WWT was found to 3.25 GWh/year at a cost of around 500 million Euros (Campanelli, M., Foladori, P. and Vaccari, 2013). The Korean Ministry of Environment (MOE) indicated that WWTPs in Korea accounted for 0.5% of the national energy consumption and was aiming to reduce their WWT grid energy dependency by 50% by the year 2030 (Chae and Kang, 2013). Israel's WWT consumes 10% of its available grid energy, and is on average tenfold higher than any other of the countries listed above. This is attributed to the fact that Israel is water-scarce country and has adopted an extensive wastewater re-use policy (Olsson, 2012). He *et al.*, (2019) projected that the electricity requirements for WWT would increase significantly within developed countries, stating that within the following 15 years the energy input could rise by 20%, placing increased strain on resources and lead to significant GHG emissions.

2.5 Global sectoral wastewater energy demand

The consensus within the scientific community is that aeration and pumping are the two leading energy consumers within the WWT process (Mizuta and Shimada, 2010; Brandt *et al.*, 2011; Shi, 2011; Olsson, 2012; Tarallo, 2015; Longo *et al.*, 2016; Smith *et al.*, 2018), however the actual opinions on what these percentages are differ remarkably. Furthermore, Walther, (2013) concluded that pumping accounted for 12% of the total energy requirements during the WWT process where others have stated that this figure is closer 20% (Mizuta and Shimada, 2010; Daw et al., 2012). Figure 2 below represents the typical sectoral energy consumption with an activated sludge WWTP (Walther, 2013).

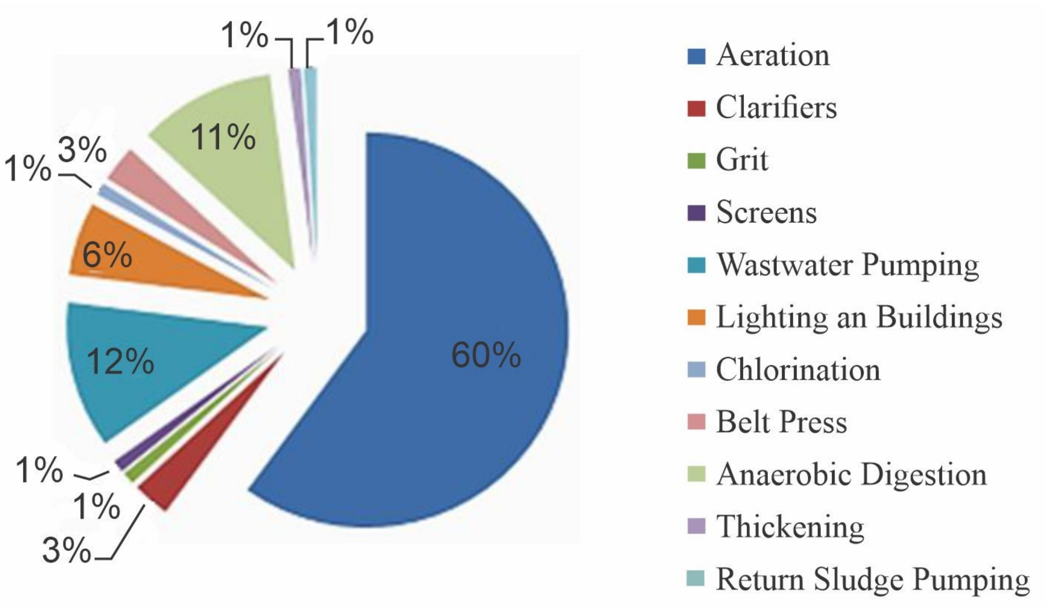


Figure 2: Sectoral energy consumption within an activated sludge WWTP (Walther, 2013)

Table 2 below indicates the sectoral percentages for aeration and WWP across the globe.

Table 2: Sectoral specific energy consumption in wastewater treatment

Countries	**Region**	**Aeration / biological reactor (%)**	**Pumping (%)**	**Reference**
Austria	*	70	4	(Jonasson, 2007)
Austria	Strass	57	9	(Jonasson, 2007)
China	Beijing	58	32	(Smith *et al.*, 2018)
Finland	Mikkeli	39.9	15.7	(Gurung, Tang and Sillanpää, 2018)
Germany	*	67	5	(Marner, Schröter and Jardin, 2016)
Iran	Tabriz	77	11	(Nouri *et al.*, 2006)
Italy	Turin	51	-	(Panepinto *et al.*, 2016)
Japan	Northern Kumamoto	46	18	(Mizuta and Shimada, 2010)
Korea	*	42	22	(Park et al., 2007)
Poland	Slupsk	53	30	(Zaborowska, Czerwionka and Makinia, 2017)

Poland	Southern region	74	6.5	(Maslon, Wojcik and Chimelowski, 2018)
Portugal	*	53	12	(Henriques and Catarino, 2017)
Singapore	*	60	12	(Gu *et al.*, 2017)
Spain	Girona	42	20	(Aymerich *et al.*, 2015)
Sweden	Stockholm	48	9	(Jonasson, 2007)

-no present data found

*data assumed representing entire region

Maktabifard, Zaborowska and Makinia, (2018) found that aeration and pumping accounted for 53% and 12%, whilst researching energy neutrality in WWTPs through methods of enhanced renewable energy production and also energy saving measures in Slupsk, Poland. Maslon, Wojcik and Chimelowski, (2018) found that the southern region of Poland the figures for aeration and pumping accounted for 74% and 6.5% of the WWT process. Mizuta and Shimada, (2010) analysed data for Northern Kumamoto WWTPs from the period of 1996 till 2007. The study concluded that pumping and conventional activated sludge operations accounted for 18% and 46% repectively. Panepinto *et al.*, (2016) studied the specific energy consumption for all electro-mechanic devices within the Castiglione WWTP in Italy. The WWTP was one of the largest facilities loacted in the country where the energy demand was estimated to be around 66.78 GWh/ year. The plant utilized conventional activated sludge and was recorded to consume 51% of the total energy requirements, with no meantion of pumping being measured. Gurung, Tang and Sillanpää, (2018) studied energy benchmarking towards a retro-fitting energy saving stategies for WWTPs in Finnland, where the sectoral percentages for WWP was found to be 15.7%. Furthermore, a WWTPs energy demand and efficiency depended on the following factors namely; location of the plant, size of the plant, type of treatment process, effluent quality standards, age of the plant and the training and knowledge of its operators (Gu *et al.*, 2017; Xu *et al.*, 2017). These factors differed worldwide as an un-unified approach to WWT was directed by countries different positions on effluent quality standards, budget limitations and policy implementation (Gu *et al.*, 2017).

2.6 Cape Town's wastewater and energy landscape

The City of Cape Town (CCT) 2021 State of Energy and Carbon Report (SECR) details the crucial factor that energy plays within the Cape Town as a City. The report is a comprehensive view of the current energy landscape in Cape Town. The report aims to move towards holistic sustainable energies sources within the various sectors of Cape Town economy. The 2021 SECR sort to replace the CCT 2015 State of Energy Report (SER), which was geared to address GHG's and climate change from a mitigation within the municipal structures standpoint. The SECRs expanded scope also addresses the energy supply chain within CCT for cleaner, sustainable energy and a Carbon-neutral energy supply chain by the year 2050 (Stone *et al.*, 2021). SECR details historic sectoral GHG and carbon emissions from the year 2012 until 2018 as per Figure 3 below:

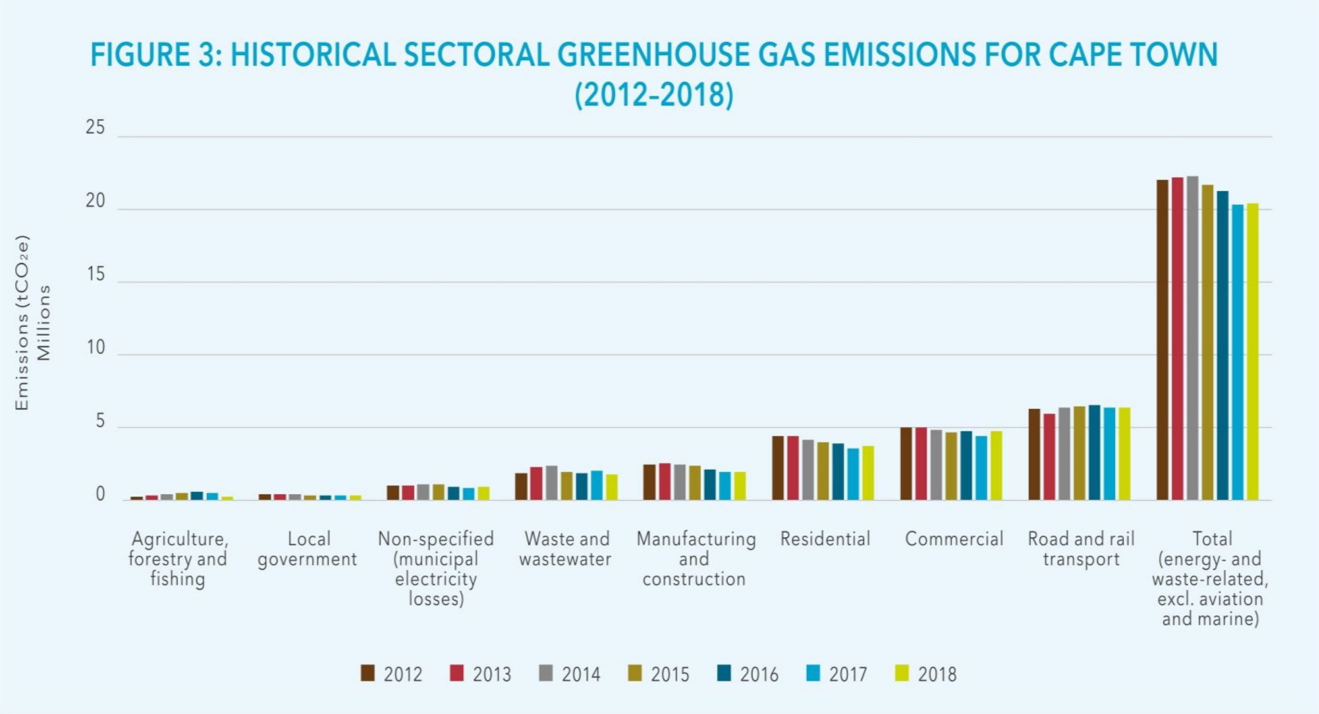


Figure 3: Cape Town's historic GHG emissions by sector (2012 -2018)(Stone et al., 2021)

The sectoral historic GHG emissions as detailed in Figure 3 above, where the CCT's wastewater's GHG emissions had displayed and steady decline from the year 2012 till 2018. The gradual decline was primarily attributed to policy shifts within the city towards energy efficiency, retrofitting and upgrading of existing WWT facilities (Manie and Johnstone, 2017; Stone *et al.*, 2021).

2.6.1 Cape Town's wastewater landscape

The CCTs 2017 Integrated Development Plan (IDP) Water Sector Input Report (WSIR) details the water landscape within Cape Town. The report indicated that the Cape Town 27 WWTPs and 9216 km of sewer reticulation pipelines treated in excess of 490 Ml /day for June 2016. The CCT had 406 PSs (both sewage and stormwater) with a total replacement value (TRV) of R1.373 billion, with an additional upgrade of three WWPSs and one new-build WWPS. The report details the importance of technological advances and investment into the CCT urban water cycle (Manie and Johnstone, 2017).

2.6.2 Cape Town’s wastewater GHG

SECR provides specific detail regarding the sectoral energy source and GHG emissions. Electricity 52.9%, diesel 16.2% and petrol 14.3% listed to be the three top primary sources of energy used within Cape Town. The top three sectoral GHG emitters was road transport, commercial and institutional and residential being 28.7%, 22.0% and 17.2%, respectively (Stone et al., 2021). Figure 4 below indicates the emissions (tCO2e) for both the city’s primary energy sources as well as economic sectors (Stone et al., 2021).

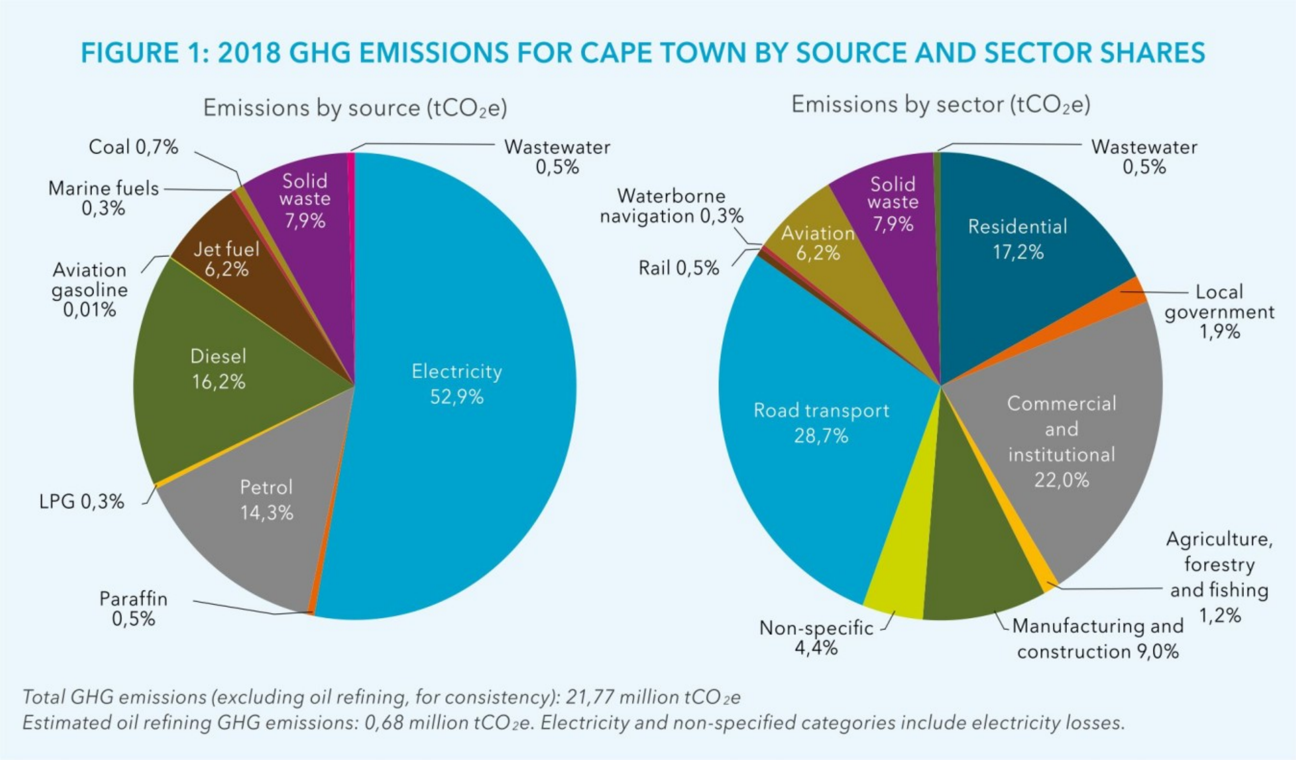


Figure 4: Cape Town’s GHG emissions by sector and energy source (Stone et al., 2021)

Cape Town’s WWT contribution was recorded at 0.5% for both the energy usage and GHG emissions for the entire city (Stone et al., 2021).

2.6.3 City of Cape Town’s energy demand for wastewater treatment and pumping

Euston-Brown *et al.*, (2015) assessed the CCT Local Municipal Government (LMG) energy consumption as a stand-alone sector. Cape Town’s LMG currently is the single largest consumer of energy within its geographical boundaries, consuming 4% of the electricity, 1% of the cities total energy and contributing to 3% of the cities GHG emissions. The sources of energy utilized by the CCT consisted mainly of petrol, diesel and electricity at 9%, 17% and 74% respectively as per Figure 5 below.

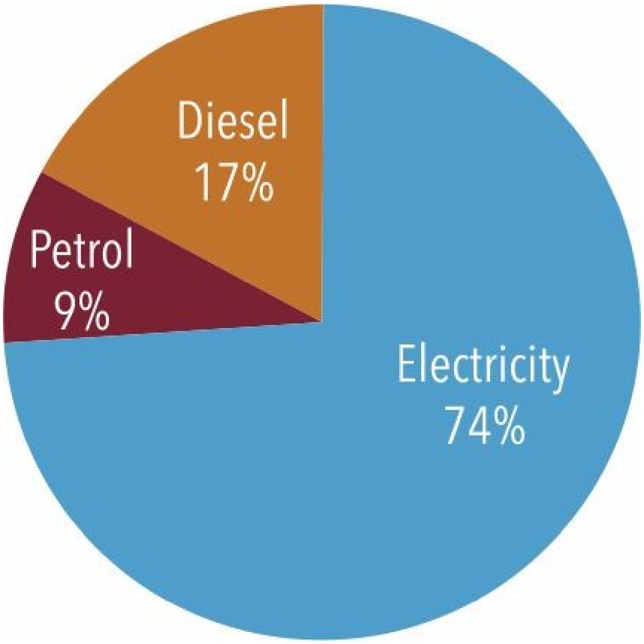


Figure 5: CCT LMG energy consumption by source for 2012 (Euston-Brown et al., 2015)

Major energy consumers within the CCT LMG were the sectors of: 1) vehicle fleet (28%); 2) street lighting 17%; 3) buildings and facilities 23% and bulk water supply 3%. WWT and pumping accounts for 21% and 8% of the total energy consumption with the CCT and traffic signalling below 1% (Euston-Brown et al., 2015). Figure 6 below indicates the sectoral energy consumption for service sectors within CCT LMG.

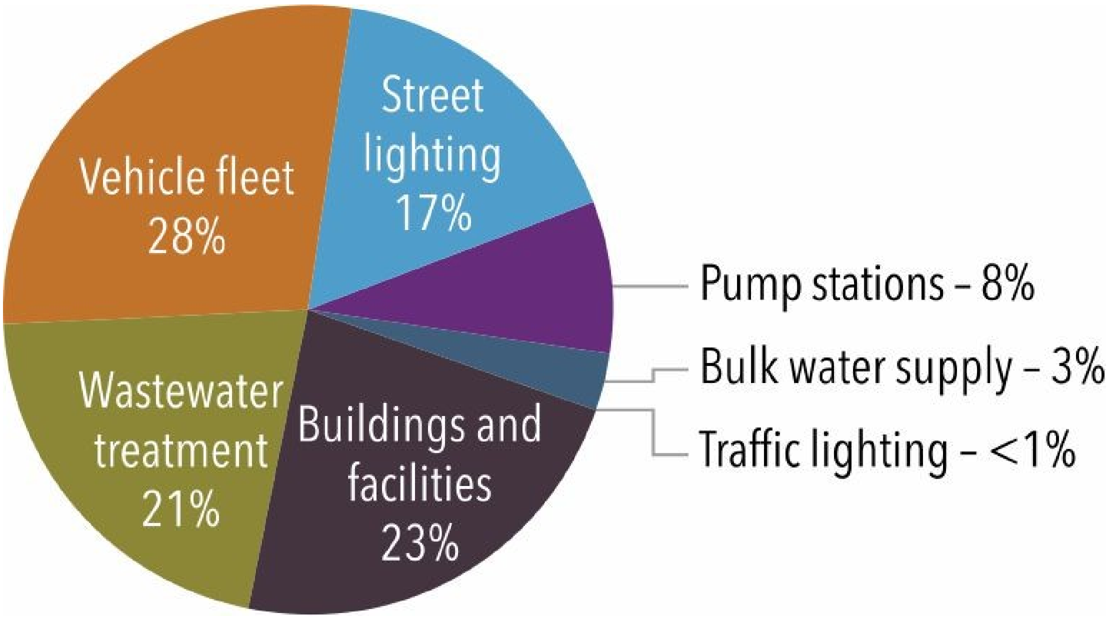


Figure 6: CCT LMG service sectors energy consumption for 2012 (Euston-Brown et al., 2015)

Major GHG emission contributors within the CCT LMG were the sectors of: 1) street lighting 21%; 2) buildings and facilities 29%; 3) vehicle fleet 9% and bulk water supply (4%). WWT and pumping accounts for 37% (27% and 10%) of the total energy consumption with the CCT and traffic signalling below 1% (Euston-Brown et al., 2015). Figure 7 below indicates the sectoral energy consumption for service sectors within CCT LMG.

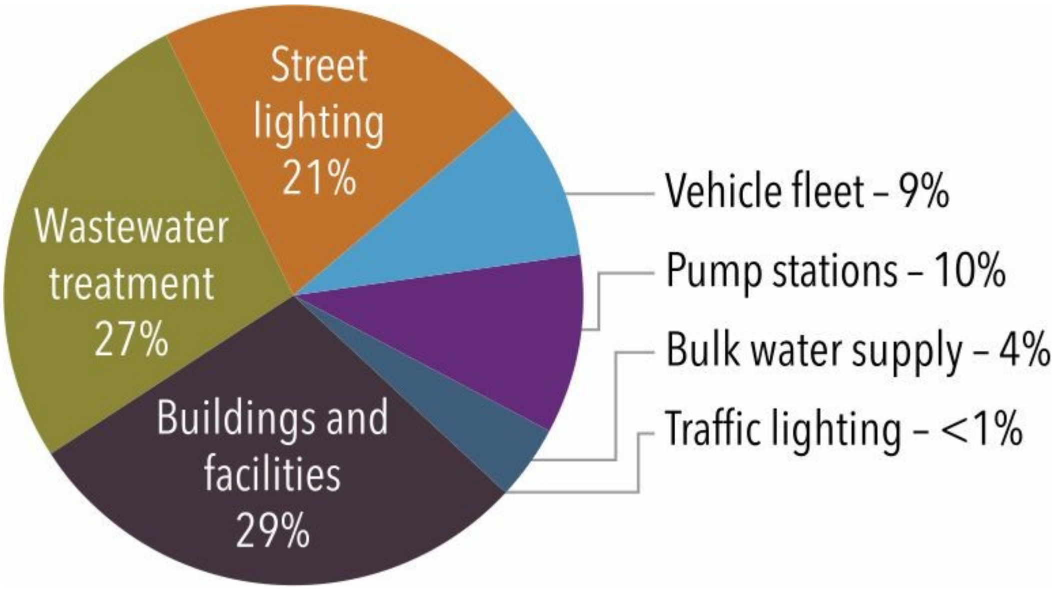


Figure 7: CCT LMG service sectors GHG emissions for 2012 (Euston-Brown et al., 2015)

Electricity usage within the CCT LMG sectors consisted of: 1) street lighting (23%); 2) buildings and facilities (32%) and 3) bulk water supply (5%). WWT and pumping accounts for 30% and 10% of the total energy consumption respectively. Vehicle and traffic signalling electricity usage were below 1% and 0% respectively (Euston-Brown et al., 2015). Figure 7 below indicates the sectoral electricity consumption for service sectors within CCT LMG.

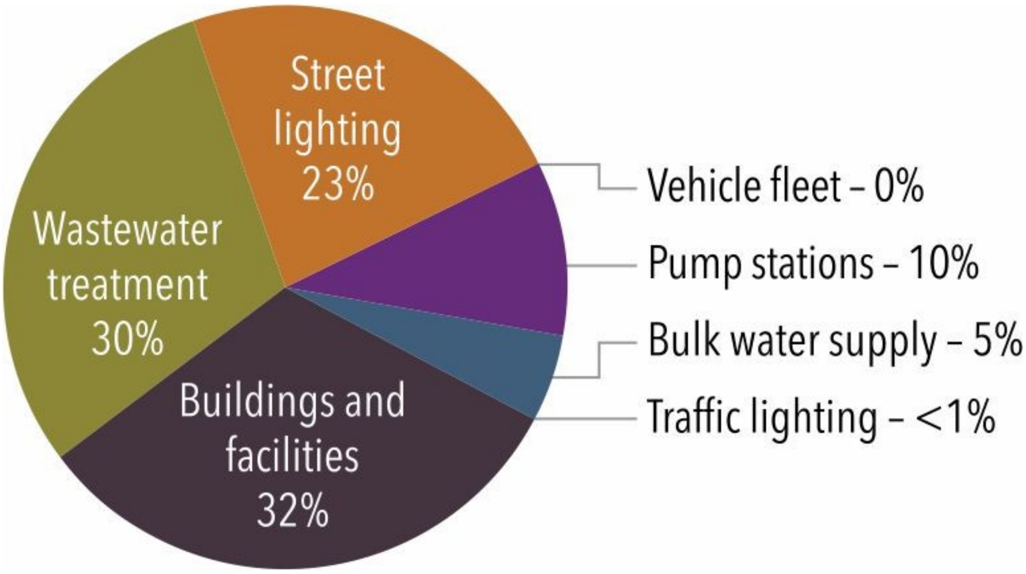


Figure 8: CCT LMG service sectors electricity consumption for 2012 (Euston-Brown et al., 2015)

From Figures 5, 6, 7 and 8 above it is noted that addressing the energy consumption of WWPS would look to redress 8% of the CCT LMG primary energy needs, 10% of the CCT GHG emissions and restore 10% of the electricity if it was substituted with RESs.

Furthermore, recent developments has seen the CCT’s WWPSs been adversely affected by loadshedding. Adams, (2022) stated that raw sewage flowed onto Cape Town’s beaches during December 2022 as a result of WWPSs being inoperable during loadsheddng. This has had a negative impact on the environment and local tourism due to beaches being closed as a result of dangerous contaminatants and poor water quality. Daniels, (2023) reported that the CCT had increased its planned capital budget for WWPSs upgrades under the Mayoral Priority Programme for water and sanitation, from R70 million in 2022, to R400 million in 2024, and R500 million in 2025 respectively, however this makes no mention of RE.

SECTION C: WASTEWATER ENERGY TOWARDS CARBON-ZERO

2.7 Wastewater treatment energy efficiency and energy recovery

Yan *et al.*, (2016) stated that the large amounts of external energy currently utilized in WWTPs was preventing these facilities from being ecologically sustainable. Singh, Carliell-Marquet and Kansal, (2012) stated that the scientific community sees energy optimization and efficiency of WWT as a popular topic. McCarty, Bae and Kim, (2011) stated that energy recovery in wastewater has increased over the past few decades. Jenicek *et al.*, (2013) has researched energy self-sufficient WWTPs and studied their reduced operational cost, energy consumption to achieve carbon neutrality. Jiang *et al.*, (2020) stated that energy efficiency in WWT is a comprehensive exercise, which requires expertise on numerous aspects such as: 1) electrical devices and equipment; 2) process control and 3) automation control. Wastewater's energy potential is recognised as an option for energy generation (Frijns, Hofman and Nederlof, 2013). Wastewater holds a noteworthy amount of potential energy and energy recovery strategies from WWT and its by-products is attracting increased attention because of its reduced environmental demands and cost (Yan *et al.*, 2016; Di Fraia, Massarotti and Vanoli, 2018). However, the principal theory of self-sustaining WWT remained the exploitation of chemical energy in the wastewater pollutants (Jenicek *et al.*, 2013).

2.7.1 Net-zero wastewater treatment plants

Xu *et al.*, (2017) analysed self-sustaining energy WWTPs through scenario analysis for WWTPs located in eastern China after calculating their respective electrical loads. Their findings indicated that self-sufficient WWTPs could be realised through energy saving technologies, which allows for greater efficiency and application of RES. WWTPs in large parts of the world are decades old, but are upgraded and retrofitted as technology has progressed towards increased effluent standards and energy efficiency (Maktabifard, Zaborowska and Makinia, 2018). An approach of upgrades towards energy neutrality is realised once wastewater effluent quality and standards are maintained and secondly the adoption of new technologies are convincing for current plant operators (Maktabifard, Zaborowska and Makinia, 2018). SPV and combined heat and power (CHP) can produce power for WWTPs and was confirmed to be a significant finding for new-build WWTPs, but also transversely applied in the transformation of existing WWTPs (Xu *et al.*, 2017). Nowak, Enderle and Varbanov, (2015) studied the foremost techniques in which a net-zero energy approach could be optimized within two cutting-edge Austrian WWTPs. Their findings indicated that by utilizing CHP, fuelled by biogas stemming from anaerobic sludge digestion, the energy production outweighed the plants energy consumption, in effect creating surplus energy, which could be fed into the grid. Jenicek *et al.*, (2013) researched net-zero WWTPs in Prague, Czech Republic, where the data revealed that energy contained in the wastewater was several times higher than what was required for its treatment. This meant that self-sustainable WWT was not only possible, purely for treatment, but also as a realistic energy source.

2.7.2 Solar photovoltaic and wind turbines in wastewater treatment

'Energy-independence' is the ratio of energy consumption to RES production and/or energy savings. These two basic principles are the cornerstones of achieving energy independence with in WWT, namely: 1) improve energy efficiency and savings opportunities and 2) utilizing RE and unexploited energy sources, (Chae and Kang, 2013). RESs appropriate to WWTPs include, but are not limited to: 1) micro-hydropower; 2) solar thermal energy; 3) SPV; 4) biogas production and 5) heat recovery for CHP (Frijns, Hofman and Nederlof, 2013). Desalination is also an extremely energy intensive process where SPV and wind power has been reliably employed in order to power operations (El-Ghonemy, 2012). Technological advances within WWTPs has seen RES of wind power, SPV, micro-hydro power and wastewater heat recovery being utilized in a combination and/or standalone energy system (Chae and Kang, 2013). In eastern China's scenario analysis, Xu *et al.*, (2017) found that the SPV energy production for the area was remarkable. Simulations had indicated that the modelled SPV system energy output for the WWTP was equal the amount of electricity required. The results concluded that 9000 m² of SPV could sustain most of the energy requirements, however the model did not consider then actual land footprint.

2.8 Wastewater treatment energy recovery in Cape Town

SECR 2021 detailed that substantial investment into SPV for WWTPs implementation across Cape Town within the following years to come. In order to achieve carbon-neutrality by 2050, several potential projects was identified, namely: 1) Kraaifontein WWTP with an estimated SPV energy production of 1752 MWh/year; Athlone WWTP with an estimated SPV energy production of 4204 MWh/year and Bellville WWTP with an estimated SPV energy production of 4555 MWh/year, but to name a few (Stone *et al.*, 2021). The CCT installed a floating SPV power generation system in Kraaifontein WWTP, a first of its kind within South Africa, where data collection over a year will aid in the understanding and design in other similar large scale projects (Hyman, 2021). Other WWTPs under consideration were Cape Flats, Mitchells Plain, Potsdam and Westfleur (Stone *et al.*, 2021).

SECTION D: WASTEWATER ENERGY BENCHMARKING

2.9 Global wastewater treatment energy intensity and benchmarking

Wastewater by definition is water polluted by solids and liquids stemming from residential, commercial and industrial use. The environmental impacts of wastewater is tremendous and its recycling requires extensive energy inputs (Wakeel *et al.*, 2016). Benchmarking energy consumption and intensities within WWT processes could be levered as a potent management tool which could utilize exact indicators to evaluate and/or locate the optimum performance when compared against other WWTPs (Krampe, 2013). At present, a worldwide WWTP energy benchmarking system does not exist at an international level (Longo *et al.*, 2016). Benchmarking and analysis aids potential energy saving opportunities and may assist in prioritization of optimization efforts (Krampe, 2013). The specific energy intensity in various countries for WWT represented in Table 2 below:

Table 3: National energy intensities associated with wastewater treatment in different countries

Countries/ Regions	**Specific energy intensity for wastewater treatment across different technologies (kWh/m³)**	**Reference**
Australia	0.460	(Gu *et al.*, 2017)
Austria	0.300	(Jonasson, 2007; Shi, 2011)
China	0.269 – 0.310	(Rothausen and Conway, 2011; Yan *et al.*, 2016)
Finland	0.180 – 0.960	(Gurung, Tang and Sillanpää, 2018)
France	0.680	(Shi, 2011)
Germany	0.400 – 0.670	(Wang *et al.*, 2016)
Hungary	0.750	(Pitas *et al.*, 2010)
Italy	0.400 – 0.700	(Guerrini, Romano and Indipendenza, 2017; Borzooei *et al.*, 2019, 2020)
Japan	0.304 – 3.740	(Mizuta and Shimada, 2010)
Korea	0.243	(Chae and Kang, 2013)
Malaysia	0.440	(Ramli and Hamid, 2017)
Netherlands	0.360	(Shi, 2011)
Saudi Arabia	1.600	(Wakeel *et al.*, 2016)
Singapore	0.550 – 0.920	(Shi, 2011)
Slovakia	0.145 -1.422	(Bodík and Kubaská, 2013)
South Africa	0.079 – 0.410	(Wang *et al.*, 2016)

Spain	0.530 – 1.800	(Wakeel *et al.*, 2016)
Sweden	0.420 – 0.630	(Jonasson, 2007; Shi, 2011)
Switzerland	0.520	(Gu *et al.*, 2017)
Taiwan	0.410	(Gu *et al.*, 2017)
Turkey	0.380 – 0.430	(Turkmenler, 2019)
United Kingdom	0.640 – 0.680	(Shi, 2011)
USA	0.330 – 0.600	(Shi, 2011; Wang *et al.*, 2016)

Chae and Kang, (2013) investigated incorporation of green renewable energy resources for municipal WWTPs in Korea. The mean energy intensity for WWT in Korea was 0.243 kWh/m^3. It was also found that a study like this could guide policy makers, planners, engineers and designers concerning renewable energy strategies for WWT. In the far east, countries such Taiwan and Malaysia are recording similar specific energy intensity levels for WWT at 0.410 kWh/m^3 and 0.440 kWh/m^3 respectively (Gu et al., 2017; Ramli and Hamid, 2017). Singapore's WWT energy intensity range is between 0.550 – 0.920 kWh/m^3, far more than compared to Taiwan and Malaysia (Shi, 2011). Moreover, Asian countries of China, Japan and Korea show lower energy intensity for WWT between 0.269 – 0.310 kWh/m^3; 0.304 – 3.740 kWh/m^3 and 0.243 kWh/m^3 respectively (Mizuta and Shimada, 2010; Rothausen and Conway, 2011; Chae and Kang, 2013; Yan et al., 2016). WWT in the USA is reported to be around 0.330-0.600 kWh/m^3 (Gu et al., 2017), whilst others are stating that this figure is around 0.520 kWh/m^3 (Wang et al., 2016). Jonasson, (2007) studied the energy benchmarking for the WWT process, comparing both Sweden and Austria. Austria's specific energy intensity was recorded at 0.300 kWh/m^3 and Sweden's ranging between 0.420 – 0.630 kWh/m^3 (Jonasson, 2007; Shi, 2011). Furthermore, an improvement of 30% in decreased electricity costs had taken place since the inception of energy intensity benchmarking had begun in 1999. Improvements in these WWTPs was found to be directly attributed to the benchmarking of the energy intensity levels. The energy intensity for conventional activated sludge WWTPs in European countries such as: France; Germany; Hungary; Italy; Switzerland and the United Kingdom (UK) all display energy intensity levels ranging between 0.400 – 0.750 kWh/m^3 (Pitas *et al.*, 2010; Shi, 2011; Wang *et al.*, 2016; Gu *et al.*, 2017; Borzooei *et al.*, 2020). The Netherlands displays a failry low energy intesity level when compared to european counterparts at 0.360 kWh/m^3 (Shi, 2011). The energy intensity levels for Spain, Slovakia and Finland ranges vastly at 0.530 – 1.800; 0.145 – 1.425 & 0.180 – 0.960 kWh/m^3 for WWT respectively (Bodík and Kubaská, 2013; Gu *et al.*, 2017; Gurung, Tang and Sillanpää, 2018). Turkmenler, (2019) invetsigated the energy efficiency at Gebze WWTP, Turkey, and found that it's energy consumption for WWT varied between 0.380 – 0.430 kWh/m^3 amounting to a volume of 2.020 x 10^6 m^3/month. Saudi Arabia made extensive use of reverse osmosis technology which is known for being a highly energy intensive process, hence recording energy intensity levels of 1.600 kWh/m³, however this also includes the removal of high levels of phosphorous which added higher intensity (Wakeel et al., 2016). South Africa extensively utilized the technologies of trickle filters and lagoon stabilization ponds, which are far less energy insensitive. However there are instances where activated sludge WWTP are found in the country (Wang *et al.*, 2016).

Energy for WWT ranges between 0.3 – 2.1 kWh/m³ worldwide (Liu, Ramnarayanan and Logan, 2004). Energy intensity levels for WWT differ all over the world as these countries makes use of different types of technology towards its treatment and this is a reason for the variance (Gu *et al.*, 2017). Vaccari *et al.*, (2018) stated that in many cases where benchmarking studies are undertaken, these studies seem disjointed and piece-meal due to the study being carried out on a locally, centred on domestic and provincial studies.

2.10 Global wastewater pumping energy intensity and benchmarking

Wastewater collection and pumping forms part of the primary treatment stage within the treatment process. The pumping stage of WWT, with respect to energy requirements for wastewater, is known to be far less energy intensive than compared with the processes of secondary and advanced stages of WWT as per the Figure 9 below (Wakeel *et al.*, 2016).

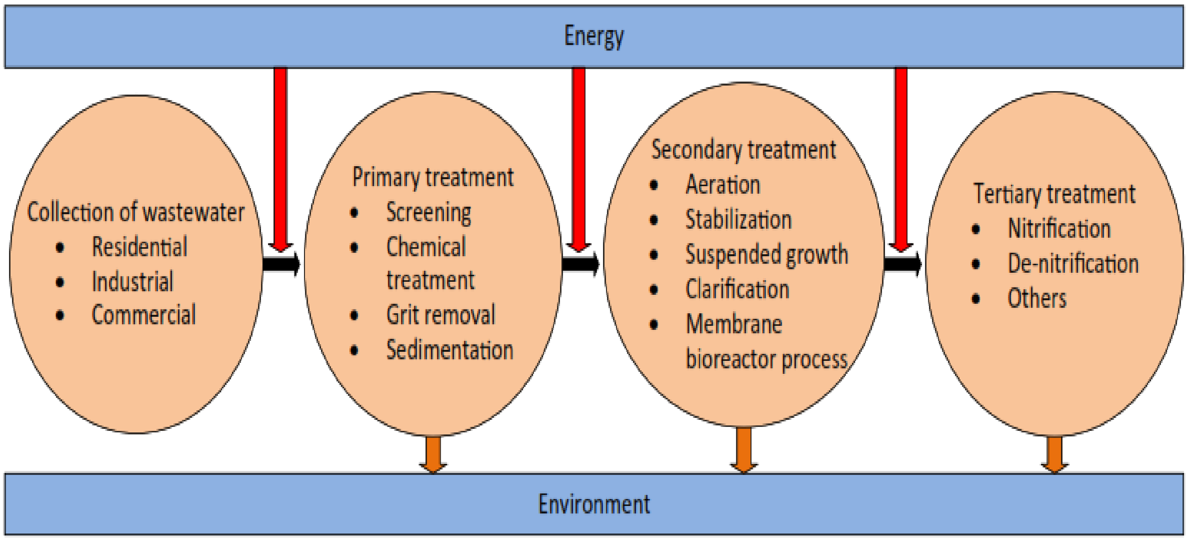


Figure 9: Energy inputs in different wastewater treatment processes (Wakeel *et al.*, 2016)

Wett, Buchauer and Fimml, (2007) recognised that WWTPs are commonly regarded as the largest individual energy users within the municipal structures and Panepinto *et al.*, (2016) estimated that this is between 25% - 40% of the operation costs of WWT was attributed to energy consumption. However, both Shi, (2011) and Tarallo, (2015) recognise and demonstrate that energy efficiency and energy recovery is possible within all stages of the WWT process. Table 4 below indicates the specific energy intensity in various countries for WWP.

Table 4: Energy intensities associated with wastewater pumping in countries

Country	**Specific energy intensity for wastewater pumping (kWh/m³)**	**Reference**
Australia	0.049 – 0.520	(Brandt *et al.*, 2011)
Canada	0.020 – 0.100	(Statistics Canada, 2018)
China	0.030 – 0.100	(Smith *et al.*, 2018)
Finland	0.072	(Gurung, Tang and Sillanpää, 2018)
Hungary	0.045 – 0.140	(Pitas *et al.*, 2010)
India	0.040 – 0.160	(Miller, Ramaswami and Ranjan, 2013)
Italy	0.032 – 0.076	(Foladori, Vaccari and Vitali, 2015)
Japan	0.048 – 0.095	(Mizuta and Shimada, 2010)
Korea	0.053	(Chae and Kang, 2013)
New Zealand	0.040 – 0.190	(Kneppers, Birchfield and Lawton, 2009)
USA	0.040	(Matos *et al.*, 2014)
BEST PRACTICE**	0.039 – 0.055	(Tarallo, 2015)

** not a country

In Europe, countries such as Finland, Hungary and Italy all display energy intensities for WWP which range between 0.032 – 0.140 kWh/m³ (Pitas *et al.*, 2010; Foladori, Vaccari and Vitali, 2015; Gurung, Tang and Sillanpää, 2018). In Asia, countries such as China , India and Korea are ranging between 0.048 – 0.160 kWh/m³ (Chae and Kang, 2013; Miller, Ramaswami and Ranjan, 2013; Smith *et al.*, 2018). For Japan, Mizuta and Shimada, (2010) found the energy intensity for WWP to range between 0.048 – 0.095 kWh/m³. Australia and New Zealand WWP energy intensity is ranging between 0.040 – 0.190 kWh/m³ (Kneppers, Birchfield and Lawton, 2009; Brandt *et al.*, 2011) and Canada ranging between 0.020 – 0.100 kWh/m³ (Statistics Canada, 2018).

2.10.1 Wastewater pumping energy intensity for cities and towns

Pumping system facilities are a beneficial resource within the municipal environment as they offer a service of collection and distribution without disturbance to the community it serves. Notwithstanding, pumping stations necessitate constant operation and maintenance costs (Davidson, Benson and Drive, 2003). WWT is a collection of several energy-intensive operations, where WWP requires substantial energy inputs in order to fuel its discharge process (Wakeel *et al.*, 2016). Table 5 below indicates various countries and regions specific energy intensities for WWP around the globe.

Table 5: Energy intensities associated with wastewater pumping in Cities

Country	**City/ Town/ region**	**Specific energy intensity for wastewater pumping (kWh/m³)**	**Reference**
USA	Austin (TX)	0.791	(Kjellsson, Greene and Webber, 2013)
China	Changzhou	0.030 – 0.100	(Smith *et al.*, 2018)
India	Delhi	0.040	(Miller, Ramaswami and Ranjan, 2013)
New Zealand	Kapiti	0.193	(Kneppers, Birchfield and Lawton, 2009)
Japan	Kumamoto	0.059	(Mizuta and Shimada, 2010)
Australia	Melbourne	0.090	(Olsson, 2012)
Finland	Mikkeli	0.720	(Gurung, Tang and Sillanpää, 2018)
New Zealand	Nelson City	0.106	(Kneppers, Birchfield and Lawton, 2009)
New Zealand	Palmerston North	0.041	(Kneppers, Birchfield and Lawton, 2009)
USA	Southern California	2.300	(Olsson, 2012)
India	Tiruchirappalli	0.160	(Miller, Ramaswami and Ranjan, 2013)
New Zealand	Waitakere	0.095	(Kneppers, Birchfield and Lawton, 2009)

Energy requirements for the pumping of wastewater to the treatment plant differ all across the world (Olsson, 2012). In Changzhou, China, Smith *et al.*, (2018) recorded the WWP energy intensity levele to range between 0.030 – 0.100 kWh/m³. Olsson, (2012) recorded notable differences in the city of Melbourne (Austrialia) and region of Southern California (USA) at 0.090 kWh/m³ compared to 2.300 kWh/m³ respectively. Other cities in the USA as Austin (Texas) was recorded to have a WWP energy intensity of 0.791 kWh/m³ (Kjellsson, Greene and Webber, 2013). Miller, Ramaswami and Ranjan, (2013) investigated the GHG contributions of water and wastewater systems operating within Indian cities and found that the GHGs was proportional to the magnitude of the cities. The study also distingushed between WWT and WWP, where Delhi's WWP energy intensity was 0.040 kWh/m³ and Tiruchirappalli at 0.160 kWh/m³. In Kumamoto, Korea, Mizuta and Shimada, (2010) found the energy intensity for WWP to be 0.059 kWh/m³ for the years between 1996 till 2007.

From the data collected above it is evident that not much is known regarding energy intensity studies of WWP at an international level, and this is true for South Africa, particularly Cape Town. Research has concluded that comprehensive efforts are required for the closing of the technological gap between developed and developing countries (Wang *et al.*, 2016). Findings have revealed that self-sufficient WWTP technology is completely feasible, however many challenges still exist with particular reference to developing countries where further efforts are required in terms of feasibility; environmental protection and addressing the technological gap, which are area’s needing exploration (Gu *et al.*, 2017).

CHAPTER 3: THEORECTICAL CONSIDERATION

This chapter seeks to justify the methodology applied to this study. This chapter will focus on case studies of energy audit data; methodologies employed by others as well as evaluating mathematical modelling software and outputs currently utilized in the industry.

SECTION E: THEORY OF WASTEWATER ENERGY BENCHMARKING

3.1 Case studies of energy auditing in wastewater treatment

Marner, Schröter and Jardin, (2016) strongly recommended that energy audits be conducted regularly in order to aid a systematic approach in obtaining the energy consumption profile of a WWTP. Tarallo, (2015) studied energy management and performance towards net-zero water facilities. From this study, benchmarking operations and treatments within various WWT processes identified along with possible energy efficiency strategies. Shi, (2011) studied mass flow and energy efficiency patterns in Singapore, with Ulu Pandan Wastewater Reclamation Plant (WWRP) as the case study. The purpose of the study was a quantitative measurement of sewage bulk flows and energy consumption patterns within sub-operations inside the WWRP. Key performances and operational energy consumption covering both solids and liquids was studied and compared to Strauss WWTP, Austria, which had a historical energy efficiency of 108% and regarded worldwide as a WWTP benchmark. From these comparisons, opportunities for energy saving and improvements was identified. Foladori, Vaccari and Vitali, (2015) studied energy consumption patterns in northern Italy over the span of two years. The study served as an energy audit where data gathered was focused on five WWTPs that was considered small as they had all served a population of around 10 000 inhabitants. Historically the energy intensity of WWTPs was measured by the amount of electricity require to treat a set volume of wastewater (Mizuta and Shimada, 2010). Vaccari, Foladori and Vitali, (2018) conducted a benchmarking study where over two-hundred (200) WWTPs was surveyed across Italy. Their findings were that the use of kWh/m³ was misleading due to the fact that WWTPs whom received stormwater could appear to be inaccurately more energy efficient, due to the fact that the pollutants was less concentrated as a result of the dilution. Borzooei *et al.*, (2020) studied WWTPs energy audit data and found that a data scarcity within the domain was limiting the application of model-based optimization techniques. Factors adding to the data scarcity was found to be, but not limited to: 1) labour-intensive methods for data collection and monitoring, leading to unpleasant aptitudes by data collection stakeholders (Borzooei *et al.*, 2020) and 2) irregular senor cleaning and maintenance, leading to erroneous data measuring and a reduction in data samples collected (Martin and Vanrolleghem, 2014).

3.2 Case studies of energy benchmarking in wastewater treatment

Gurung, Tang and Sillanpää, (2018) evaluated Finnish WWTPs in order to benchmark their energy consumption and identify retrofitting strategies towards energy efficiency. The methodology employed was that of statistical analysis where the energy intensity of WWT was found to be 0.49 kWh/m³ with a standard deviation of 0.197 for Mikkeli WWTP, Finland. Gurung, Tang and Sillanpää, (2018) stated that although Mikkeli WWTP utilized several different types of energy e.g. chemical; manual; mechanical and electrical, however the electrical was the primary energy source and the focus of the study. Two key parameters identified within the study was: 1) volume of wastewater (m³) and chemical oxygen demand (COD). The two relevant energy-benchmarking indicators were volume of wastewater 1) kWh/m³ and 2) kWh/COD, calculated as follows:

$$Energy\ consumption\ per\ unit\ of\ treated\ wastewater\ \left[\frac{kWh}{m^3}\right] = \frac{\left[energy\ consumption\ \left(\frac{kWh}{day}\right)\right]}{\left[treated\ wastwwater\ \left(\frac{m^3}{day}\right)\right]} \tag{3.1}$$

$$Energy\ consumption\ per\ unit\ of\ COD\ \left[\frac{kWh}{kg\ COD}\right] = \frac{\left[energy\ consumption\ \left(\frac{kWh}{day}\right)\right]}{\left[COD\ removed\ \left(\frac{kg\ COD}{day}\right)\right]} \tag{3.2}$$

Niu *et al.*, (2019) studied the factors influencing energy intensity levels of WWTPs in China in a bid to gain understating and aid improvement in the areas of WWT planning and management in order to cope with increasing standards of treatment and growing levels of pollution. The energy intensity of WWT in China was significantly higher than that of other countries. Niu *et al.*, (2019) stated that the significant factors influencing WWT energy intensities was found to be, but not limited to: 1) technology utilized; 2) scale of treatment; 3) standard of treatment effluent; 4) loading factor; 5) sludge volume; 6) age of the plant; topography and collection area. The formulas of 3.1 and 3.2 above, used to gauge energy intensities in WWT and establish benchmarks, were also recognised by others in their studies (Wang *et al.*, 2016; Niu *et al.*, 2019; Turkmenler, 2019). Longo *et al.*, (2016) evaluated literature on the subject of energy consumption in WWT. A key finding was that no standardized global approach to energy evaluation and performance of WWTPs existed. Longo *et al.*, (2016) also found that there was three different types of energy benchmarking methodologies, which were: 1) normalization; 2) statistical techniques and 3) programming techniques, where the pros and cons of each are discussed. The normalization approach is a simplistic approach, which evaluates a WWTP under normal conditions, detailing energy performance indicators such as energy consumption against treated volumes of wastewater. The statistical approach utilizes frontier analysis in terms of a regression model, where input operational data parameters such as α and β can be placed in order to gain a simple linear regression function.

$$E = \alpha + Y\beta + \varepsilon i \tag{3.3}$$

Where, *E (N x 1)* is the energy usage of N amount of plants (for any KPI), *Y (N x m)* denotes the operation design data, which in this case would mean energy data e.g. (kWh/day) and daily inflow (m³/day). Furthermore, β (m x 1) denotes the slope coefficient for *m* different data and inputs on *N* plants, and *εi* represents the error term for the function (regression line). The statistical approach is also a simplistic method of predicting performance of a WWTP. The majority of WWT energy efficiency research conducted thus far has involved the methodology of ‘programming techniques’, where mathematical programming software simulate scenarios under different conditions and variables. The advantages of utilizing such software was no danger to the WWTP in running these simulations. Figure below indicates the three approaches to energy benchmarking within the WWT process (Longo *et al.*, 2016).

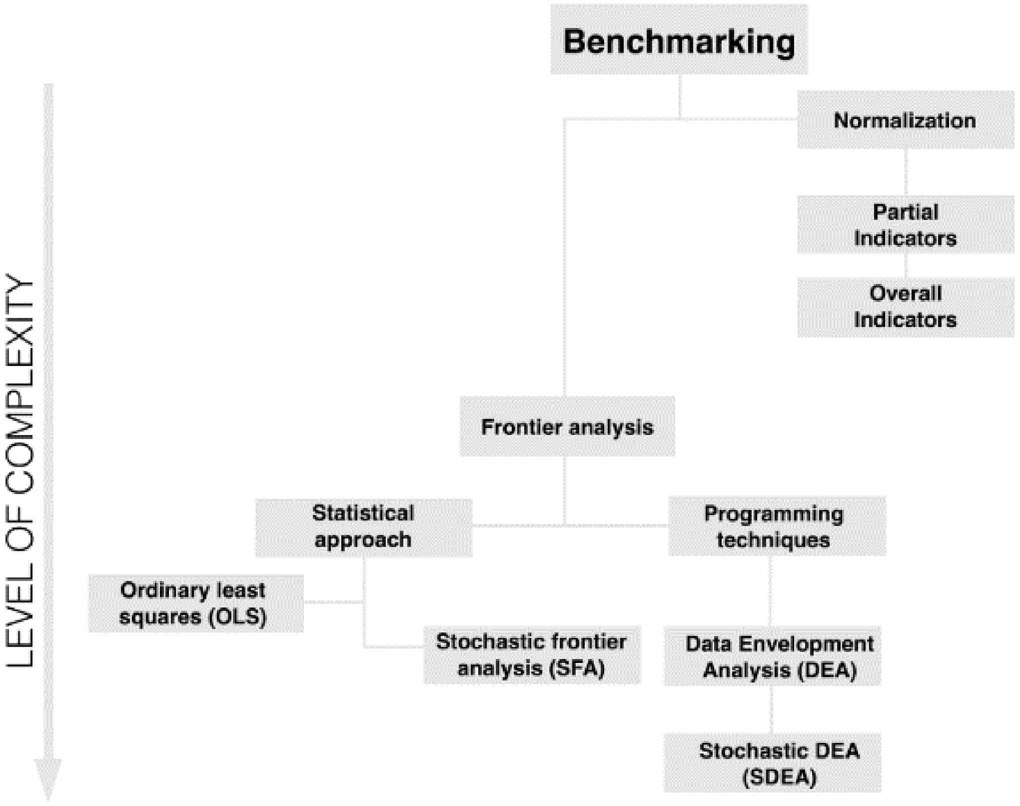


Figure 10: WWT process benchmarking analysis (Longo et al., 2016)

Longo *et al.*, (2016) furthermore provided clarity on key performance indicators (KPIs) of energy intensity benchmarking such as 'kWh/m³' and 'kWh/kgCOD$_{removed}$' among others. Table 6 below summarized the appropriate application of KPIs for energy intensities within the different stages of WWT.

Table 6: Comparison of most widely utilized KPIs (Longo *et al.*, 2016)

KPI	**Overall**	**Pre-treatment**	**Primary Treatment**	**Secondary treatment**	**Tertiary treatment**	**Sludge treatment**	**Comments**
kWh/m³	*	√√	*	*	√	*	Influent dilution and pollution removal is not considered
kWh/PE year	*	*	*	*	*	*	Pollutant removal is not considered
kWh/kg COD$_{removed}$	√	*	√	√	*	*	Limited plants with the same function
kWh/kg TSS$_{removed}$	*	*	√√	*	*	√√	Limited to primary and/or sludge treatment
kWh/kg N$_{removed}$	√	*	*	√	*	*	Limited to WWTPs where N removal is implemented
kWh/kg TPUs $_{removed}$	√√	*	*	√√	√√	*	Allow the comparison of WWTPs regardless of treatment intensity

√√ : universally acceptable
√ : not universally acceptable
* : not acceptable

From Table 6 above, we see that the KPI of kWh/m³ is a universally acceptable for a benchmark standard for the processes of primary WWT. This would apply to WWP as well because WWPSs does not serve to remove any contaminants from the wastewater, but merely convey it to the WWTP. Key parameters such as chemical oxygen demand (COD); total suspended solids (TSS) and nitrogen (N); total power usage (TPU), within the KPI, focuses on the energy intensities for these chemicals removal. Population equivalent (PE) is a more appropriate KPI for energy planning and consumption within the wastewater treatment framework and not suitable for as WWTP KPI.

SECTION F: WWTP MATHEMATICAL MODELLING AND CASE STUDIES

3.3 Hybrid Optimisation of Multiple Energy Resources (HOMER)

Hybrid Optimisation of Multiple Energy Resources (HOMER) is mathematical modelling software developed by the National Renewable Energy Laboratory (NREL) seeking to address the problem of convoluted software models on the market (El-Saadawi et al., 2010; Abo-Al-Ez, 2019). The benefits of employing software modelling such as HOMER to energy professionals are, but are not limited to: 1) optimization and performance processes towards the cluster of generating systems, e.g. biomass; wind turbines; SPV arrays etc., 2) for loading demand; economic feasibility; operating cost and 3) performance of sensitivity analysis where external factors may revise the optimization outcomes. HOMER is an industry trusted mathematical modelling software. The program is considered the benchmark in determining accuracies in performing and comparing: design optimization that determines configurations dispatch and load managing approaches towards the minimizing of cost to the operating life cycle for a specific site location and application (El-Saadawi et al., 2010).

3.4 Case studies of HOMER utilized for wind and SPV systems in South Africa

Raji and Kahn, (2012) reviewed shared energy resources for domestic user markets for the case studies of Johnnesburg and Cape Town South Africa. HOMER was utilized to condunct simulations of wind and SPV generation systems and configurations. The results for Cape Town indicated a strong potential for wind energy resource exploitation in the coastal environment. However the electricty production costs was higher in the hybrid wind-SPV system compared to the wind system, when modelling against a domestic usage energy profile.

3.5 Case studies of HOMER utilized in wastewater treatment

From the case studies below, we observe that several researchers have applied the HOMER modelling software to model RES requirement within the WWTP context.

3.5.1 Case study 1: Dynamic modelling of RES in Toukh WWTP, Egypt

Helal, Ghoneim and Halaby, (2013) researched the application of RESs towards self-sustainment for the rural WWTP of Toukh Centre-Qalyobia, Egypt. Their principal objective of the study was to establish the feasibility of a standalone RE system, satisfying the criteria of lowest life cycle cost and carbon emissions. Their finds were that rural areas within Egypt are challenged with an absence of grid connectivity because of the vast distances and remote locations, therefore a standalone systems approach would be more plausible. A second reason was that self-sustaining power was increasingly appealing, due to the rise in energy costs, as wastewater treatment was an energy intensive exercise. The methodology involved uploading the primary load data and hourly loading profile into the software with the aim to match the energy requirements. Figure 11 below indicates the hourly energy loading profile for Toukh Centre-Qalyobia WWTP.

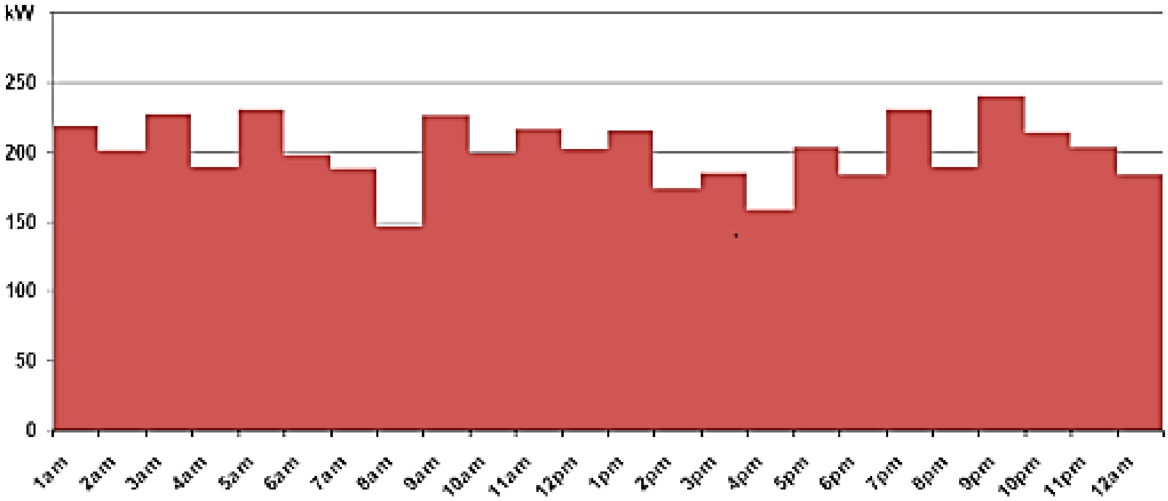


Figure 11: hourly electrical loading profile of Toukh Centre-Qalyobia WWTP (Helal, Ghoneim and Halaby, 2013)

The proposed energy system consisted of CHP units, which was fuelled by utilizing digester gas produced from sludge through the anaerobic digestion process. The energy system also utilized wind turbines and SPV along with battery storage compliment. Figure 12 below is the final configuration modelled for the sustainable energy requirements.

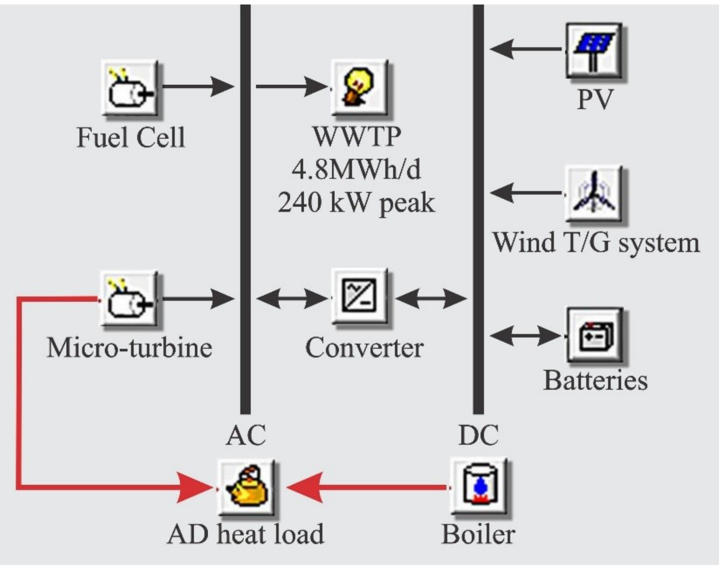


Figure 12: HOMER simulated configuration for Toukh Centre-Qalyobia WWTP (Helal, Ghoneim and Halaby, 2013)

Helal, Ghoneim and Halaby, (2013) found that the application of RE self-sustaining systems, within the context of rural remote locations for WWT, was strongly dependant on stout wind and solar resource potentials.

3.5.2 Case study 2: Dynamic modelling of RES in Wisconsin WWTP, USA

Abbas *et al.*, (2018) studied the Wisconsin WWTP in Milwaukee, USA. They stated that high volumes of flows, emanating to and from WWPTs, where exploitable opportunities for the utilization of hydro-turbines along the flow network. WWTPs presented this prospect of hydro-turbines due to the differences in elevation, exploitation gravitational flow. A case study was conducted where patterns flows where computed and simulated through HOMER. Figure 13 below is the sewage flow pattern of Wisconsin WWTP, USA.

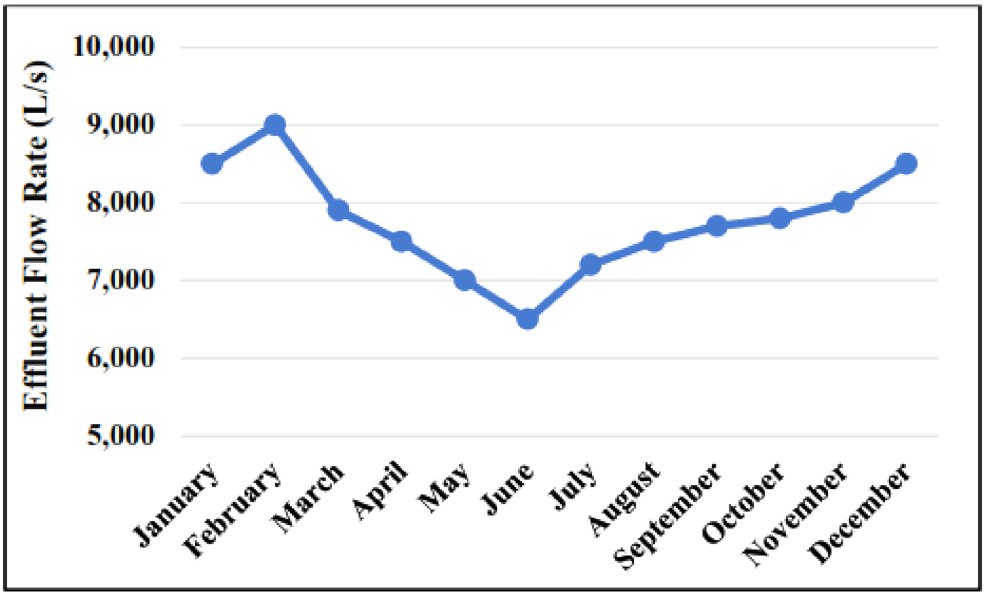


Figure 13: Average daily effluent flow volumes for Wisconsin WWTP (Abbas et al., 2018)

In summary, their findings revealed a generational capacity of 1564 MWh/year for the WWTP was possible with a head of 3.0m and an average daily flow rate of 7.750 m^3/sec for a 270 kW turbine simulated via HOMER.

CHAPTER 4: RESEARCH METHODOLOGY

This chapter explains methodology applied to this study. This chapter will focus on research design and equipment for recording energy and flow data. The methodologies as to how the data is correlated into a benchmark are detailed. The methodology of data mathematically modelled and simulated, is show.

4.1 Research design

Both the CCT's Water and Sanitation Directorate (WSD) and the Energy and Climate Change Directorate (ECCD) were approached in January 2020 in a bid to be granted permission to obtain primary data on WWPSs with the city boundaries. Quality data would enable certain and definite conclusions to be drawn within the study concerning energy benchmarking and modelling (Helal, Ghoneim and Halaby, 2013; Borzooei *et al.*, 2020). According to Longo *et al.*, (2016) three appropriate methodologies could be applied to this study, with the use of primary data, being: 1) a normalization study ; 2) a statistical study and 3) programming study. All three of these techniques are explored in this study. These methods of research design was ultimately decided upon because of its ability to provide the type of data that is in-line with quantitative research. All three of these techniques are closely linked and complement each other with regards to providing definitive answers and conclusions, and also far less likely to be biased.

4.2 Research methodologies

This portion of the study is two parts; namely: 1) the methodology for WWT energy benchmarking and 2) methodology of use of mathematical software modelling for RESs for WWPSs. The energy benchmarking will deal with the 'a normalization study' and 'statistical study', where the mathematical modelling with will dealt with under a 'programming study'. The selection of these case studies for data collections are detailed in Part 1 and 2, respectively. Table 7 below summarizes the four WWPSs and data collected as case studies and the type(s) of methodology applied. The methodology of how these PSs was selected is detailed in Part 1 and 2 below.

Table 7: Cape Town WWPSs case studies and methodologies applied

WWPS case study	Data Utilized	Year	Methodology	Reference
PART 1				
Wood Drive	Energy consumption (kWh) & WW pumped (m³)	2021	normalization and statistical study	(Longo *et al.*, 2016; Gurung, Tang and Sillanpää, 2018)
PART 2				
Royal Road	Energy consumption (kWh)	2021	programming study	(Raji and Kahn, 2012; Helal, Ghoneim and Halaby, 2013; Abbas *et al.*, 2018)
Hartleyvale	Energy consumption (kWh)	2021	programming study	
Parade Chalets	Energy consumption (kWh)	2021	programming study	

PART 1: METHODOLOGY OF WASTEWATER ENERGY BENCHMARKING

4.3 Energy benchmarking of Cape Town's wastewater pumping stations

The case study of Wood Drive WWPSs data is evaluated for the benchmarking portion of this study. The PS is only one of five WWPSs fitted with flow measuring and data logging devices within the CCT, measuring daily sewage flow patterns. In late 2019, the PS was also fitted with an electronic smart meter able to measure and data log the WWPSs specific energy consumption. However, the PS did not form part of the CCTs Smart Facility programme. In terms of a normalization and statistical study for an energy benchmark, Wood Drive WWPS is deal, because of its data logging ability to record flow and energy consumption.

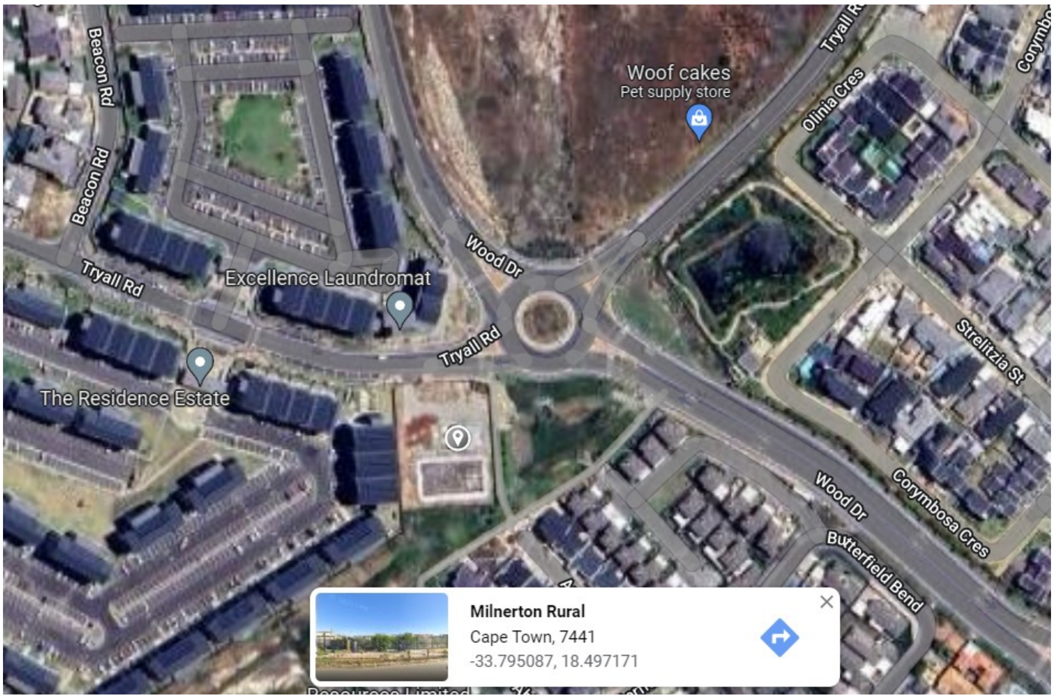
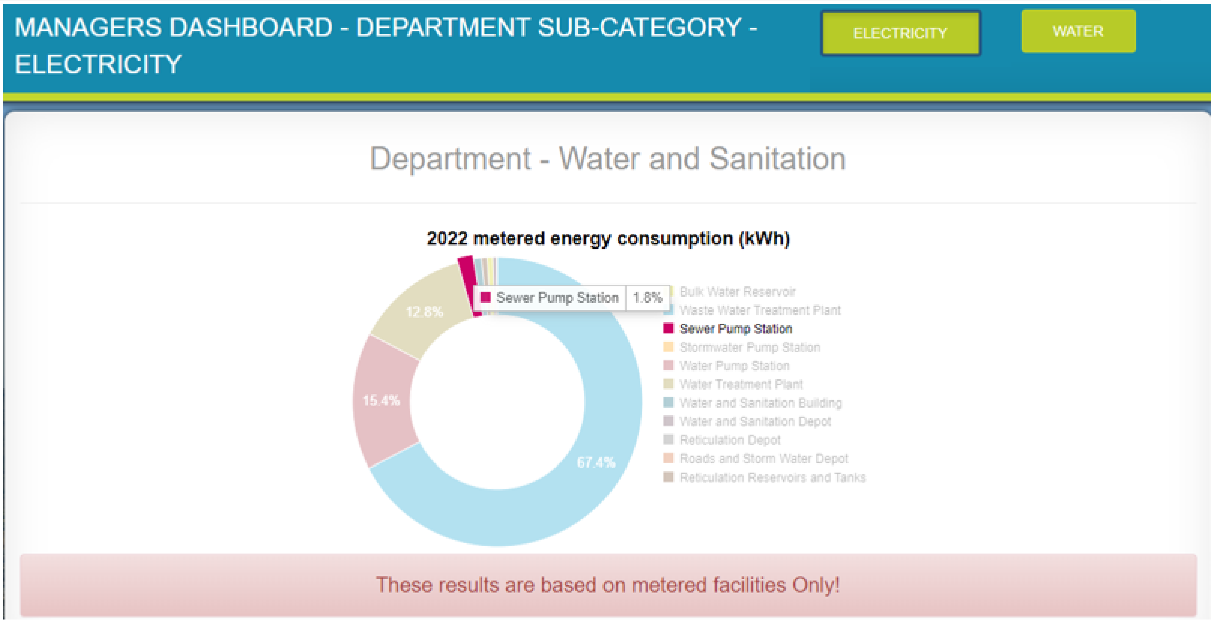


Figure 14: Locality map of Wood Drive WWPS in Parklands Cape Town

The WWPS represents 0.25% of the sample of Cape Town's WWPSs. Liu, Ramnarayanan and Logan, (2004) stated that WWT energy intensities do not differ much globally and the same is demonstrated for global landscape of WWP energy intensities as per Tables 4 and 5. It is also a finding of Borzooei *et al.*, (2020) that the collection of energy data and monitoring is a labour intensive process. From the findings of Liu, Ramnarayanan and Logan, (2004) and Borzooei *et al.*, (2020) it is clear that an exercise greater than one WWPS will be increasingly costly exercise with not much foreseen added value.

4.3.1 CCT's Smart Facility

In 2009, funding was granted to the CCT towards the City Operations Smart Electrical Metering Project with the aim of understanding electricity consumption with municipal amenities. The project has been running from 2009 until July 2021 at a cost of R9 million totalling 1190 meters installed in approximately 850 LMG buildings. The project has installed the Ladis Gyr automated meter reader (AMR). The AMR is equipped with a subscriber identity module (SIM) card used to communicate via the cell phone network with a meter data unification system (MDUS) where these reading are collected and stored. The data acquisition would allow CCT LMG to rollout strategic energy saving and efficiency projects. Since then, the CCT has internalized the budget for the implementation of smart meters within LMG facilities. Subsequent to this, Smart Facility, a localized city intranet data management platform, was launched so that facility managers within the CCT could access metered data via user-friendly dashes and generate various reports. The project was co-ordinated and funded by CCT's Sustainable Energy Markets Department (SEMD) assisted by CCT's Electricity Generation and Distribution (EGD), both departments of ECCD, for the meter installation by their artisans and technicians. EGD tests and commissions each meter according to standard and maintains the meters during their life cycle. Figure 15 below is a screenshot of the CCTs Smart Facility Dash (SFD) for the WSD, however several other departments and facilities data could be accessed from this platform.



MANAGERS DASHBOARD - DEPARTMENT SUB-CATEGORY - ELECTRICITY

Department - Water and Sanitation

These results are based on metered facilities Only!

Figure 15: Smart Facility Managers Dash

4.3.2 WWPS equipment

The research design of this study aimed to utilize equipment within the pumping station with the aim of: 1) saving cost of hiring expensive equipment and 2) relying on existing industry equipment for accurate data over a study period of 12 months.

4.3.2.1 Energy recording meter

The Landis Gyr E650 is and AMR, which provides both reliable metering data and efficient billing. The billing and data management allows for the tracking and recording of a large variety of quantities. The monitoring network allows for instantaneous monitoring of values against benchmarks and enables the recording of deviancies to log selected occurrences and disturbances. The meter allows data analysis in order to aid preventative maintenance and detect meter tampering. The software allows for customized parameter setting and application needs such as, but not limited to: billing lists, remote parameter modification and profile memory (*Landis+Gyr E650 - Landis+Gyr*, 2022). Figure 16 below is that of the Landis Gyr E650 AMR.

Figure 16: Landis Gyr E650 electricity meter

The Landis Gyr E650 has a proven record of accomplishment with over 80 countries in the world utilizing it with over two million meters installed.

4.3.2.2 Inflow measurement reader

Wood Drive WWPS is equipped with an Endress and Hauser Prosonic S FDU91 flow measurement sensor. The sensor is located in the wet-well area of the PS for the purpose of ultrasonic measurement. The sensors design allows for uninterrupted, non-contact of fluid level measurement 1) over stockpiles, 2) on belts in crushers and materials in silos. The Prosonic FDU91 and FDU91F models are able to conduct flow measurements in exposed channels and weirs with a maximum depth measurement for 10.0 m in fluids and 5.0 m in stockpiled materials respectively. The apparatus permits precise measurements in the presence of temperature fluctuations for time-of-flight corrections (*Ultrasonic measurement - Prosonic FDU91F | Endress+Hauser*, 2022). Figure 17 below is the Prosonic S FDU91 Ultrasonic measurement sensor.

Figure 17: Prosonic S FDU91 Ultrasonic measurement

4.3.2.3 Inflow data logger

The Endress and Hauser Ecograph TRSG35 Universal Graphic Data Manager (UGDM) is a data logging device with an extensive range of uses listed, but not limited to the monitoring of: 1) developments in power stations; 2) quality and quantity in the WWT industry and 3) recording and displaying crucial procedure parameters and tank and level measurement. The device is versatile and is equipped with 12 universal inputs able to record a comprehensive array of measuring signals. The 5.7-inch screen presents the ability to measure values in a maximum of four groups with digital, bar graph and curve display with a 100 msec scan rate for all channels. The device holds both internal memory and external secure digital (SD) card data archiving for safe and reliable storage. These two are both tamper-proof and allows data transferring to an external standard query language (SQL) database, preventing manipulation. The material testing before failure (MTBF) range is between 52 years and 24 years, where the calculations are based on the SN29500 standard at 40°C. Technicians are informed, via e-mail notifications, of event alarms and limit transgressions (*Ecograph T RSG35 - Universal Graphic Data Manager | Endress+Hauser*, 2022). Figure 18 below is the Ecograph TRSG35 UGDM.

Figure 18: Ecograph T, RSG35 Universal Graphic Data Manager

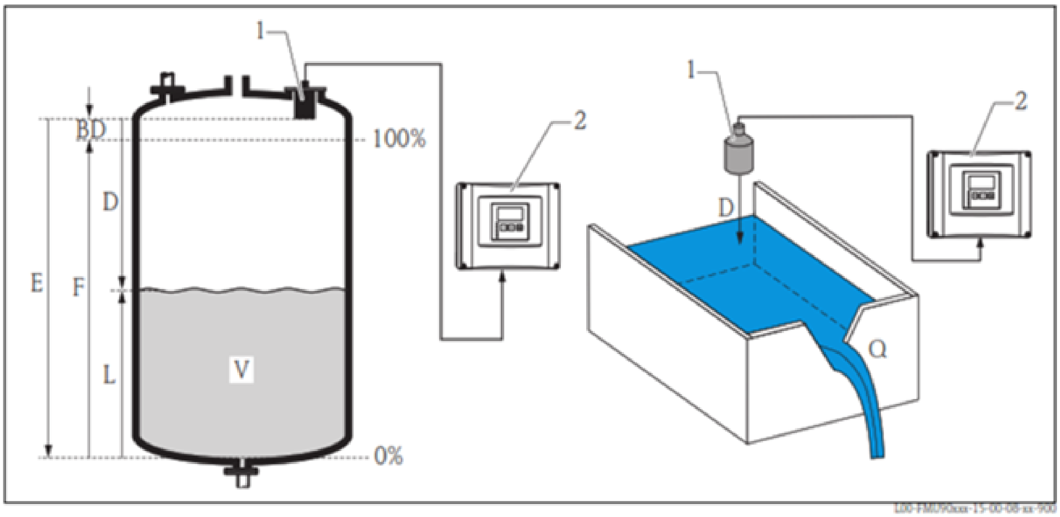


Figure 19: Prosonic S FDU91 Ultrasonic and Ecograph TRSG35 Universal Data Manager installation

Figure 19 above, demonstrates 1) Prosonic S FDU91 Ultrasonic measurement and 2) Ecograph TRSG35 UGDM where: BD = blocking distance, D = distance from sensor membrane to fluid surface, E =empty distance, F = span (full distance), L = level, V = volume (or mass), Q = flow.

4.3.3 WWPS data

This portion of the study details methodology pertaining to wastewater flow and energy data collection.

4.3.3.1 WWPS inflow data

For this section, we will assume that the sewage inflow into WWPS will equal the amount flowing out of the WWPS, as the flow measurement device is located at the influent section of the WWPS. Figure 20 below is a cross sectional plan of Wood Drive WWPS.

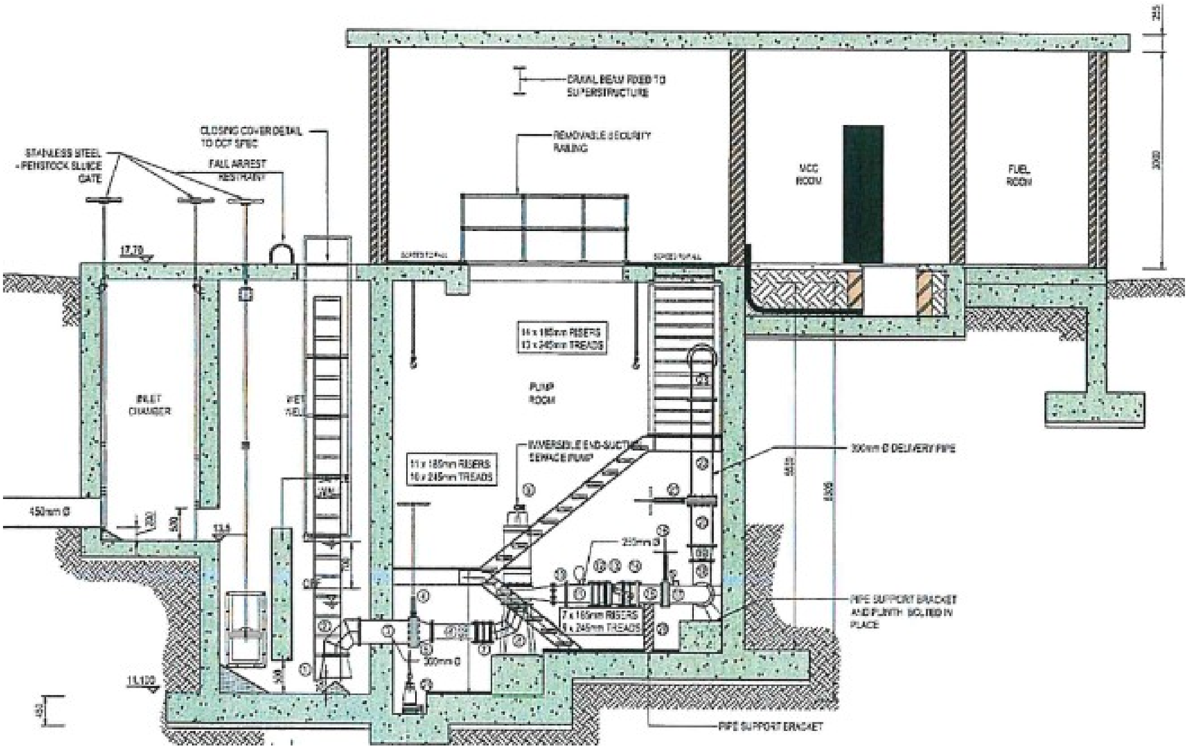


Figure 20: Cross-section of Wood Drive WWPS

A further assumption is that sewage losses within the WWPS is negligible and therefore considered zero, as indicated in the formula below:

$$Q_{\text{in}} = Q_{\text{out}} + Q_{\text{losses}} \tag{4.1}$$

Where: Q_{in} = sewage inflow (m³); Q_{out} = sewage outflow (m³) and Q_{losses} = 0.0 m³. The data for sewage flow measurement was retrieved on the location via the use of a flash drive inserted into the Ecograph T, RSG35 UGDM's universal series bus (USB) port. The data retrieval time was dependant the amount of data and the time e.g. several months' worth of data would likely take several hours. The study period for the data collected was from 00:00 am on 01 January 2021 till 11:59 pm on 31 December 2021. The data obtained, in the form of a comma-separated values (CSV) file. The file was converted to excel format to extract the primary data, namely the daily flow rates and times. The new Excel file will display the Excel converted data, where units of measure require further conversation in terms of the formula 3.1. Furthermore, the average flow/day, measured in litres/second. This is converted into a flow of m³/day by multiplying data reading of each day (l/sec) by a factor of 86.4 (10^3 x 60x60x24), yielding as result of m³/day for the entire study period.

4.3.3.2 WWPS energy data

The energy consumption data of Wood Drive WWPS was not found on CCT SFD as this was not a part of the projects, however the PS was equipped with a Landis Gyr E650 AMR and was linked to the MDUS. The energy consumption data was obtain in Excel format for the period of 00:00 am 01 January 2021 until 11:59 pm 31 December 2021. The Landis Gyr E650 AMR was set to sample the energy consumption at 30-minute intervals. The daily energy consumption data is calculated as the sum of all the 30-minute samples divided by two.

4.3.4 WWPS flow vs energy

A normalization and statistical study, conducted via Excel, was done in order to graphically to establish the correlation between the variable data sets of flow (m³/day) and energy consumption (kWh/day). The study matched that dates of the time period and utilized the daily flow and energy consumption reading as per Equation 3.1 re-iterated for clarity.

$$Energy\ consumption\ per\ unit\ of\ treated\ wastewater\ \left[\frac{kWh}{m^3}\right] = \frac{\left[energy\ consumption\ \left(\frac{kWh}{day}\right)\right]}{[treated\ wastwwater\ \left(\frac{m^3}{day}\right)]}$$

An example of this is demonstrated in Table 8 below.

Table 8: Example of daily energy consumption and in-flow data for period

Date	m³/ day	kWh/day
01-01-21	393.9	51.18
02-01-21	388.7	48.96
03-01-21	387.6	81.42
04-01-21	293.6	46.08
07-01-21	231.7	172.8
08-01-21	383.2	71.82
09-01-21	270.5	81.72
10-01-21	296.6	90.72
11-01-21	386.0	82.32
12-01-21	388.9	83.1
13-01-21	391.4	53.88
14-01-21	384.7	52.56
15-01-21	390.1	51.96
16-01-21	392.0	50.4
17-01-21	390.9	53.64
18-01-21	395.3	58.26
19-01-21	393.7	51.42
20-01-21	397.1	68.1
21-01-21	172.1	34.92

Table 8 is an example of collating the inflow and the energy consumption data collected for period. Table 9 below is an example of the calculated daily specific energy intensity (kWh/m³) as described in formula 3.1.

Table 9: Calculated daily specific energy intensity

Date	kWh/m³
01-01-21	0.130
02-01-21	0.126
03-01-21	0.210
04-01-21	0.157
07-01-21	0.746
08-01-21	0.187
09-01-21	0.302
10-01-21	0.306
11-01-21	0.213
12-01-21	0.214
13-01-21	0.138
14-01-21	0.137
15-01-21	0.133

The normalization study is demonstrated by employing Excels ‘standard deviation s’. The statistical study is further graphically demonstrated by using the daily specific energy data in the ‘Insert Chart’ ‘Scatter’ plot function where this can be observed in Figure 21 below.

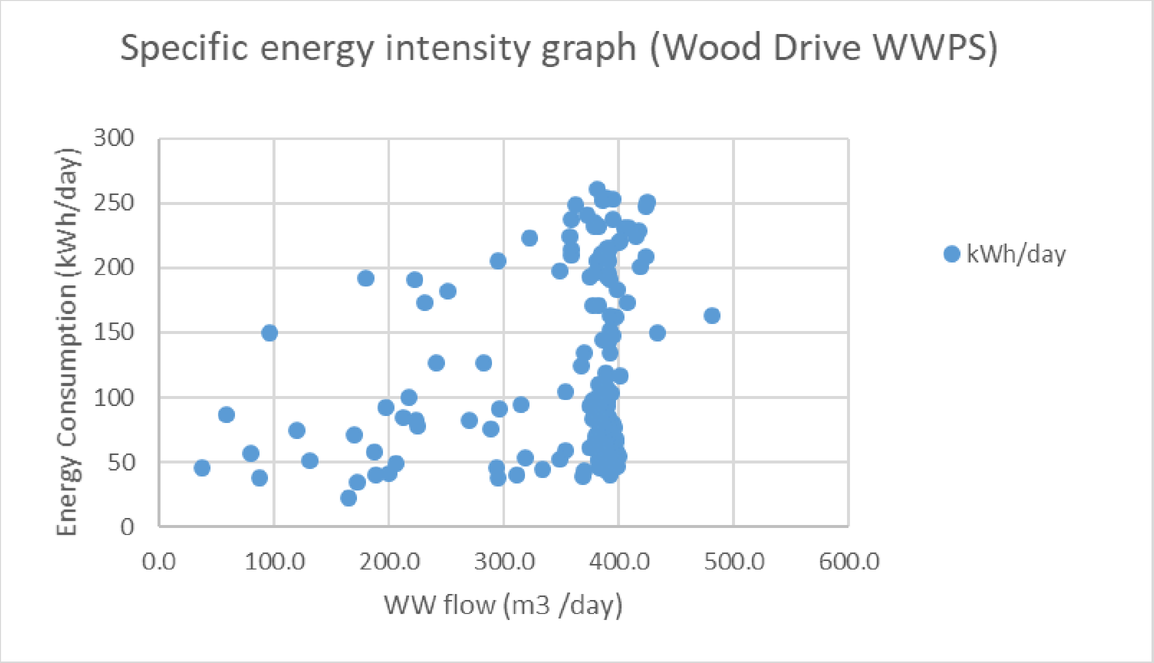


Figure 21 Energy against flow scatter plot graph for Wood Drive WWPS (2021)

PART 2: METHODOLOGY OF MATHEMATICAL SOFTWARE MODELLING FOR WWPSs RE SYSTEMS

4.4 Smart Facility energy consumption summary of WWPSs

The case studies of Royal Road, Parade Chalets and Hartleyvale WWPSs data is evaluated for the software-modelling portion of this study. Theses PSs formed part of the CCTs Smart Facility programme measuring and logging energy consumption within municipal facilities. These three case studies would be ideally suited for this study due to the yearly energy consumption profile being available. The methodology of how these PSs was selected is detailed below.

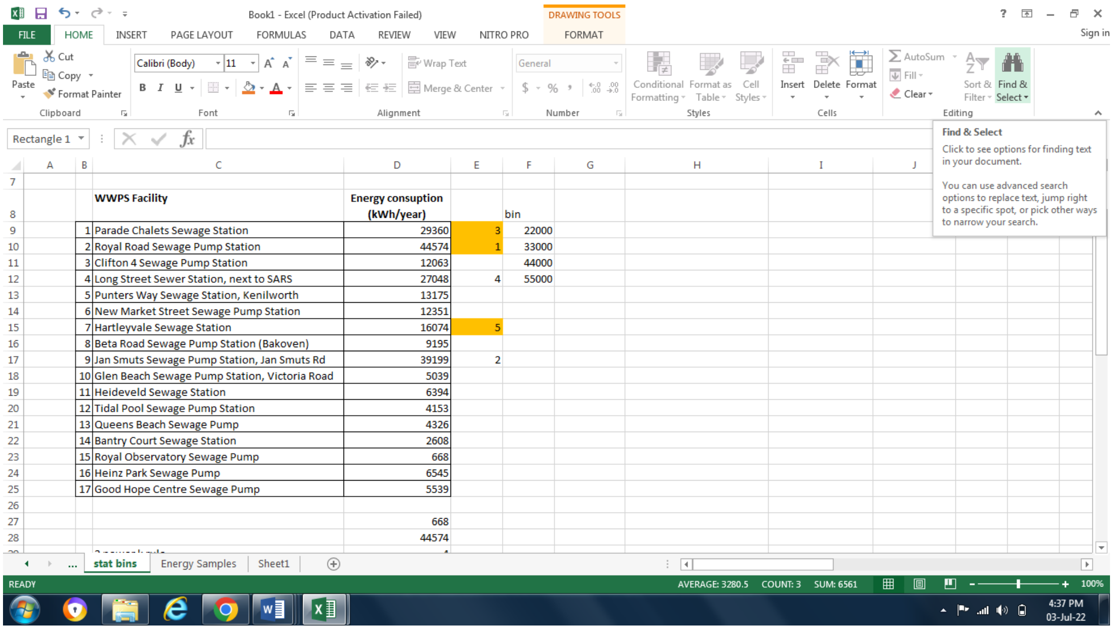
4.4.1 Statistical grouping of WWPSs according to energy consumption

Table 10 below lists the WWPSs on the CCTs SFD where the year energy consumption is indicated for the years 2020 and 2021. The listing is actually of twenty WWPSs, however the facilities of Raapskaal, The Range and Sacks Circle was omitted due to them having no data available on the platform. For the purpose of the histogram the single largest yearly energy consumption was selected for the years 2020 and 2021 and indicated in Table 10 below.

Table 10: WWPSs on CCT Smart Facility Dash

	WWPS Facility	**Energy consumption (kWh/year)**
1	Parade Chalets Sewage Station	29360
2	Royal Road Sewage Pump Station	44574
3	Clifton 4 Sewage Pump Station	12063
4	Long Street Sewer Station	27048
5	Punters Way Sewage Station, Kenilworth	13175
6	New Market Street Sewage Pump Station	12351
7	Hartleyvale Sewage Station	16074
8	Beta Road Sewage Pump Station (Bakoven)	9195
9	Jan Smuts Sewage Pump Station, Jan Smuts Rd	39199
10	Glen Beach Sewage Pump Station, Victoria Road	5039
11	Heideveld Sewage Station	6394
12	Tidal Pool Sewage Pump Station	4153
13	Queens Beach Sewage Pump	4326
14	Bantry Court Sewage Station	2608
15	Royal Observatory Sewage Pump	668
16	Heinz Park Sewage Pump	6545
17	Good Hope Centre Sewage Pump	5539

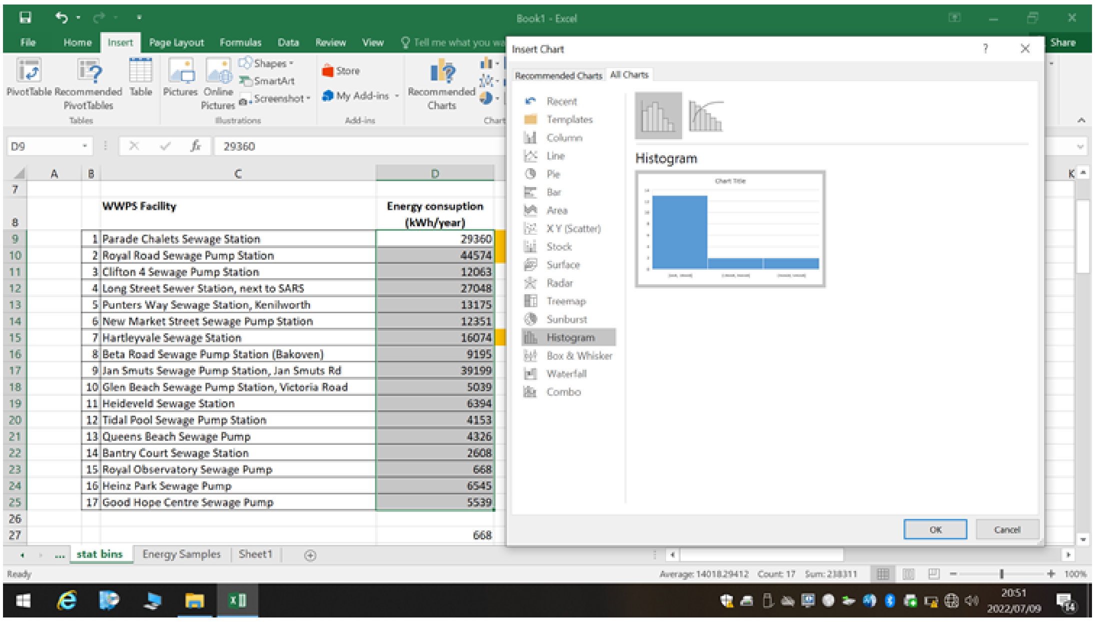
Software-modelling for all seventeen WWPS towards RES, is unpractical for the purpose of this study, due to the scale and infinite amount of variables. In order to select of which PSs to model in HOMER, Microsoft Excel was utilized to apply statistical binning to aid the selection process. The largest energy consumption within each bin would indicate as to which PS to model. Figure 22 below indicates the highlighted data of energy consumption.



	WWPS Facility	Energy consuption (kWh/year)		bin
1	Parade Chalets Sewage Station	29360	3	22000
2	Royal Road Sewage Pump Station	44574	1	33000
3	Clifton 4 Sewage Pump Station	12063		44000
4	Long Street Sewer Station, next to SARS	27048	4	55000
5	Punters Way Sewage Station, Kenilworth	13175		
6	New Market Street Sewage Pump Station	12351		
7	Hartleyvale Sewage Station	16074	5	
8	Beta Road Sewage Pump Station (Bakoven)	9195		
9	Jan Smuts Sewage Pump Station, Jan Smuts Rd	39199	2	
10	Glen Beach Sewage Pump Station, Victoria Road	5039		
11	Heideveld Sewage Station	6394		
12	Tidal Pool Sewage Pump Station	4153		
13	Queens Beach Sewage Pump	4326		
14	Bantry Court Sewage Station	2608		
15	Royal Observatory Sewage Pump	668		
16	Heinz Park Sewage Pump	6545		
17	Good Hope Centre Sewage Pump	5539		
		668		
		44574		

Figure 22: Energy consumption data highlighted in Excel

Excel has a function histogram, under the 'insert chart' 'graph' function. Figure 23 below is a screenshot of the process.



	WWPS Facility	Energy consuption (kWh/year)
1	Parade Chalets Sewage Station	29360
2	Royal Road Sewage Pump Station	44574
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10	Glen Beach Sewage Pump Station, Victoria Road	5039
11	Heideveld Sewage Station	6394
12	Tidal Pool Sewage Pump Station	4153
13	Queens Beach Sewage Pump	4326
14	Bantry Court Sewage Station	2608
15	Royal Observatory Sewage Pump	668
16	Heinz Park Sewage Pump	6545
17	Good Hope Centre Sewage Pump	5539
		668

Figure 23: Excel histogram function for highlighted data

Figure 24 below is the histogram resulting from the statistical binning of the yearly energy consumption data for the WWPSs on the CCT SFD.

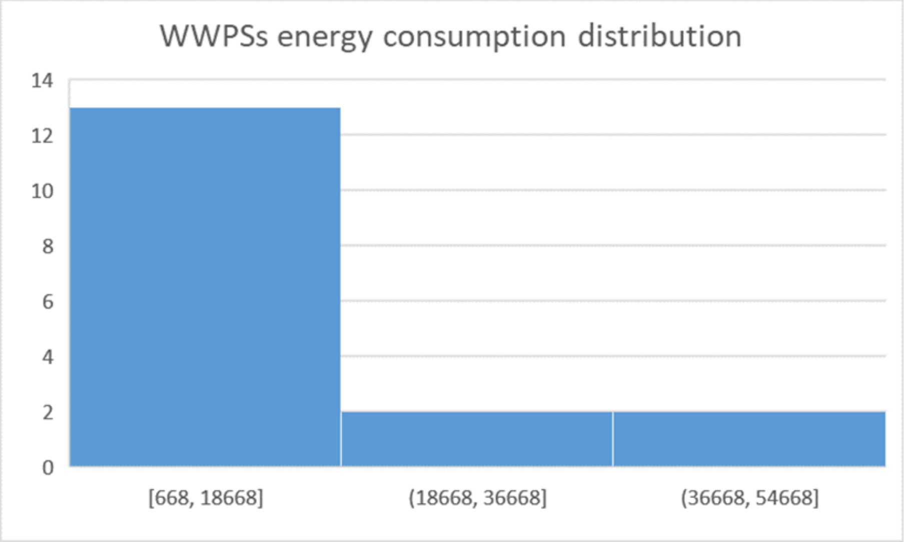


Figure 24: Energy consumption distribution histogram for SFD WWPSs

The three bins was grouped with a maximum of 18668; 36668 and 54668 kWh/year, which resulted in the selection of Royal Road WWPS (44574 kWh/year); Parade Chalets WWPS (29360 kWh/year) and Hartleyvale WWPS (16074 kWh/year) which will be modelled inside HOMER using the energy consumption data for the year 2021. The year 2021 energy consumption profiles was decided upon due to factors of Covid lockdowns playing a factor in the year 2020 and would be assumed to have a distorted result.

4.5 Software modelling of Hybrid Optimization of Electric Renewables (HOMER)

HOMER software was used to model the stand-alone wind and SPV systems for Royal Road; Parade Chalet and Hartleyvale WWPS. Where the year 2021 historical energy profile was uploaded into the programme in order to simulate a RES able to match their energy requirements. The methodology for all three PS's is the same and the steps in modelling is followed below.

4.5.1 Yearly energy data profiles of WWPS from CCT Smart Facility

Critical data is required in order to model the RES against the PSs energy consumption profile. We access SFD in order to obtain the information as per Figures 25 and 26 below. Figure 27 below lists the WWPSs on the CCTs SFD where the year energy consumption is indicated for the year 2021.

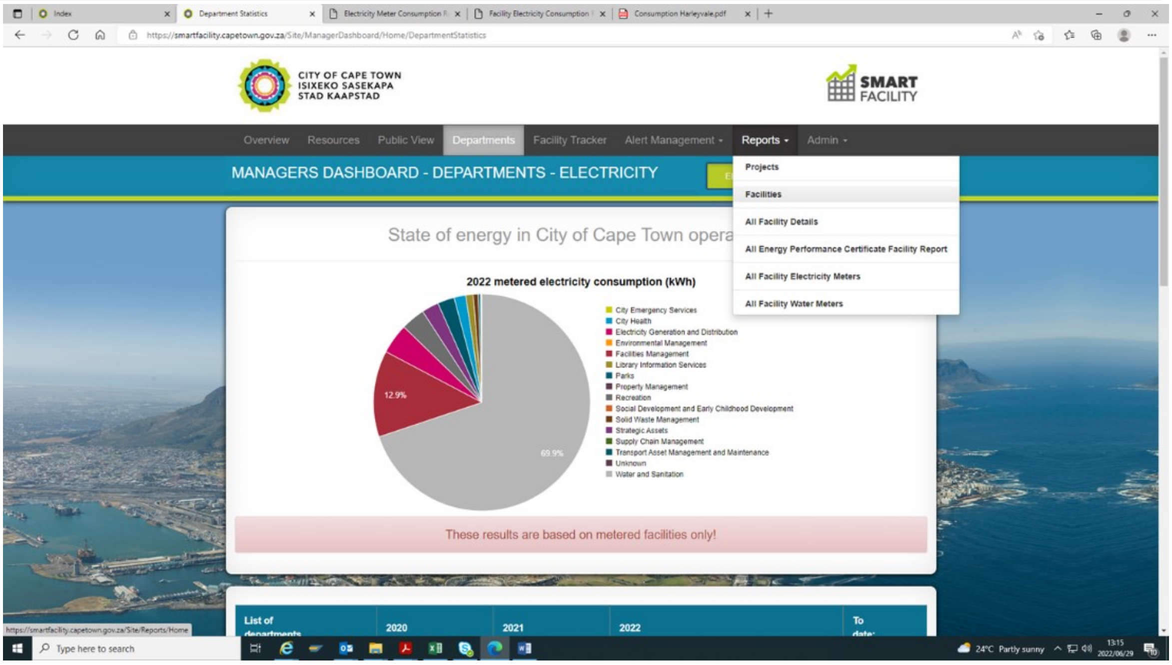
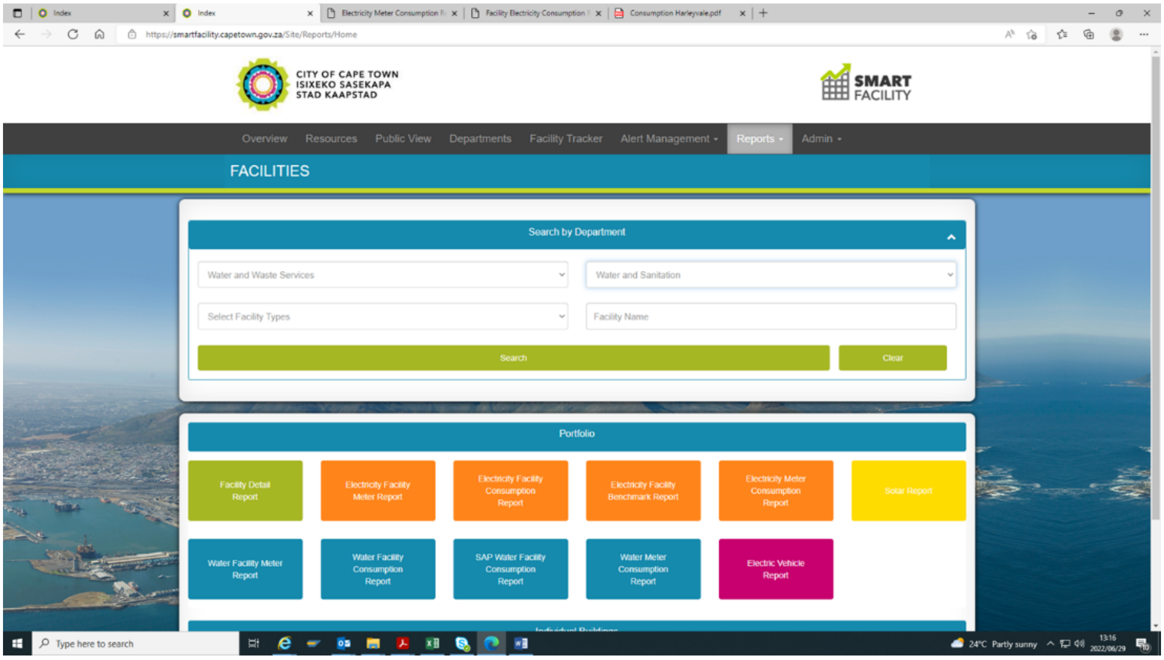


Figure 25: Smart Facility Department dash

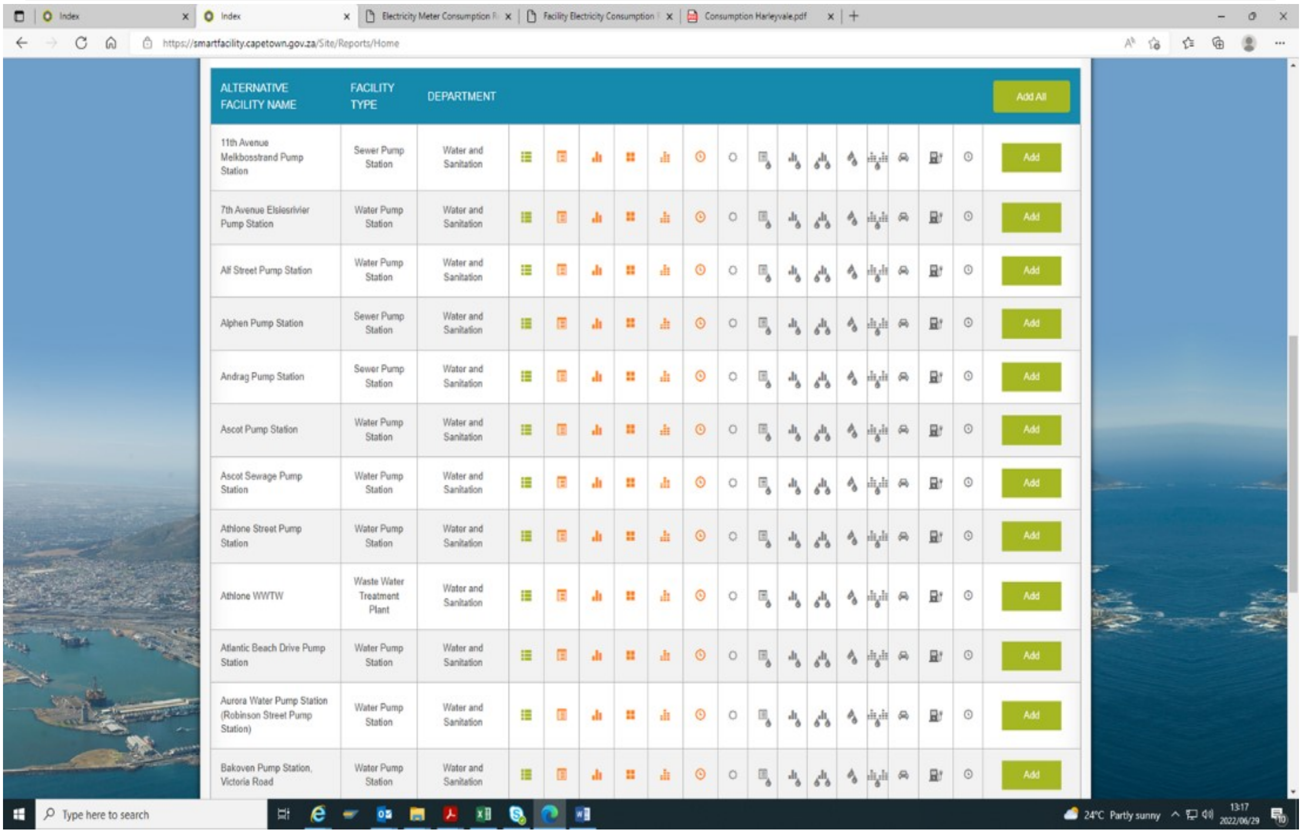
We then select the ‘reports’ tab as shown in Figure 25 above and are able to select the data of any CCT LGM facility on the SFD program. We then select the Directorate owning the facility on the drop-down an proceed to populate as much data as required in order for the SFD to select which facilities to list as per Figure 26.



Water and Waste Services
Water and Sanitation

Figure 26: Smart Facility reports

In order to select the WWPSs CT LGM facility on the SFD program, we then select the Directorate owning the facility on the drop-down an proceed to populate as much data as required in order for the SFD to select which facilities to list as per Figure 26.



ALTERNATIVE FACILITY NAME	FACILITY TYPE	DEPARTMENT
11th Avenue Melkbosstrand Pump Station	Sewer Pump Station	Water and Sanitation
7th Avenue Elsiesrivier Pump Station	Water Pump Station	Water and Sanitation
Alf Street Pump Station	Water Pump Station	Water and Sanitation
Alphen Pump Station	Sewer Pump Station	Water and Sanitation
Andrag Pump Station	Sewer Pump Station	Water and Sanitation
Ascot Pump Station	Water Pump Station	Water and Sanitation
Ascot Sewage Pump Station	Water Pump Station	Water and Sanitation
Athlone Street Pump Station	Water Pump Station	Water and Sanitation
Athlone WWTW	Waste Water Treatment Plant	Water and Sanitation
Atlantic Beach Drive Pump Station	Water Pump Station	Water and Sanitation
Aurora Water Pump Station (Robinson Street Pump Station)	Water Pump Station	Water and Sanitation
Bakoven Pump Station, Victoria Road	Water Pump Station	Water and Sanitation

Figure 27: FSD WWPS facilities report along with all the reports that one is able to select

Figure 27 above lists all the WWT facilities on the CCT SFD of which energy consumption reports could be generated.

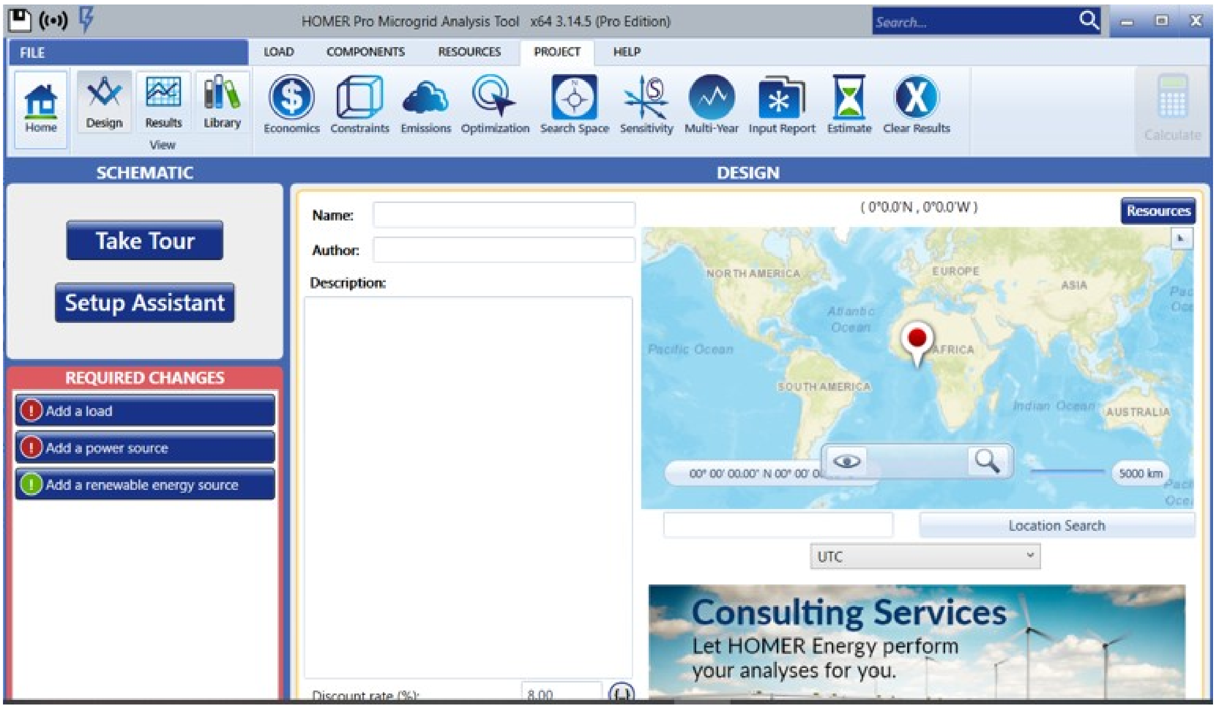
4.5.2 HOMER modelling

HOMER requires several input variables in-order to run its simulations and select the most feasible RES model. Table 11 below is a summary of the input sensitivity variables selected for the all three WWPSs of Hartleyvale, Parade Chalets and Royal Road in order to run the simulations.

Table 11: Input variables for HOMER sensitivity analysis

Sensitivity input	**Unit**	**Project variables**						
Discount rate	%	0						
Project life span	years	20						
Diesel price	R/Liter	R26.50						
Grid power price	R/kWh	R2.50	R2.75	R3.00	R3.25	R3.50	R3.75	R4.00
Sell back price	R/kWh	R0.00						
SPV project life span	years	25		20				
Battery storage	years	20		20			15	
Converter life span	years	25		20			15	
Wind life span	years	20				15		
Wind hub height	m	12						

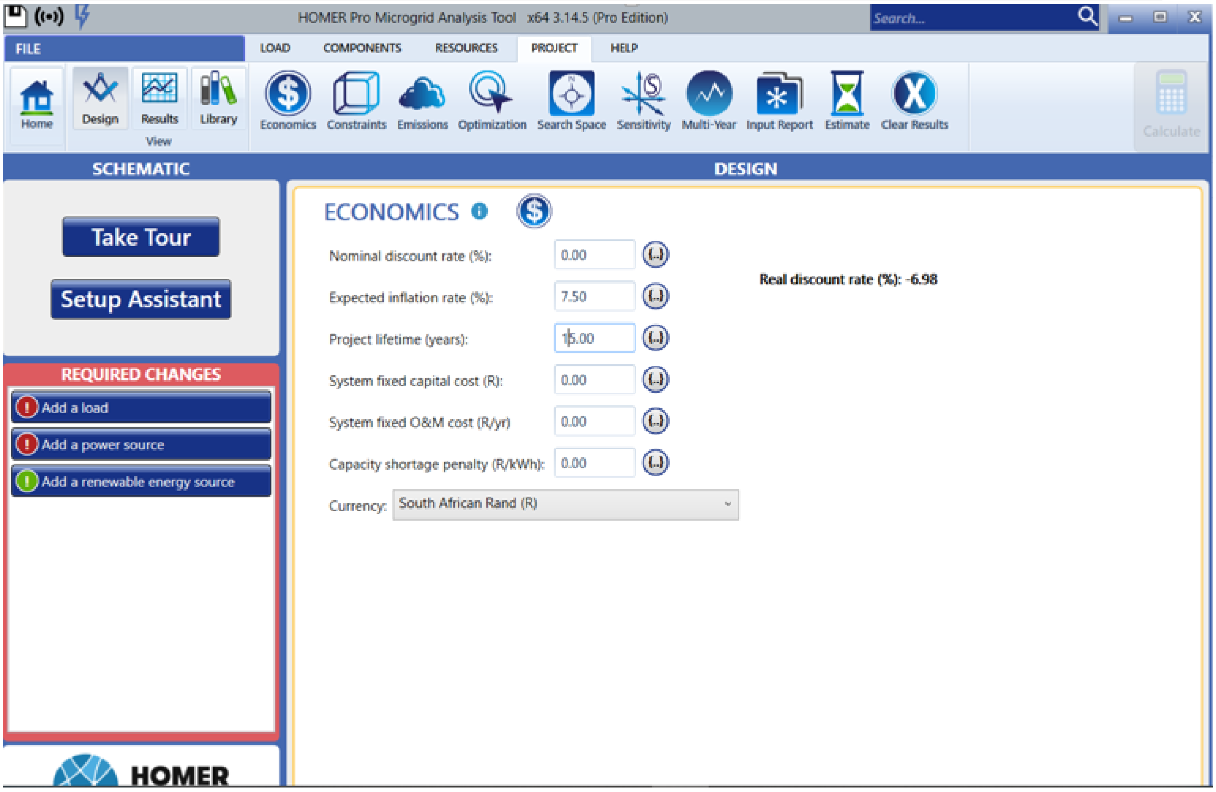
The project variables or sensitivity analysis would have to consider the cost of electricity over a span of the project. An assumption was forecasted for the price of electricity of between R2.50 to R4.00/kWh over this period based on historical market trends in South Africa. Figure 28 below is the HOMER start-up page.



Discount rate (%): 8.00

Figure 28: Example of HOMER start up page

HOMER allows one to adapt the economics under the project tab allows one to adapt to the projects specific location. Project factors like the project life span, inflation rate and the currency can be set according as per Figure 29 below.



Nominal discount rate (%): 0.00

Expected inflation rate (%): 7.50

Project lifetime (years): 15.00

System fixed capital cost (R): 0.00

System fixed O&M cost (R/yr): 0.00

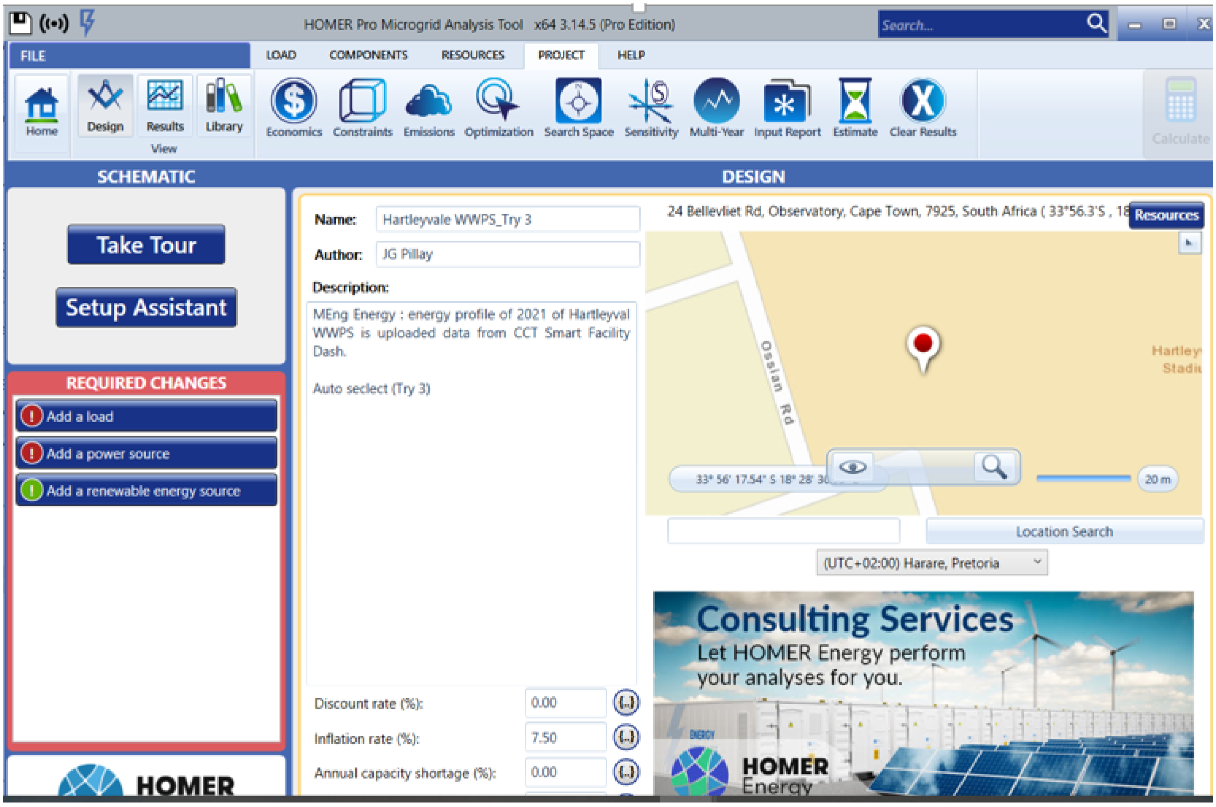
Capacity shortage penalty (R/kWh): 0.00

Currency: South African Rand (R)

Real discount rate (%): -6.98

Figure 29: Example of economics selections tab

The ‘search location’ tab enables it’s user to identify the precise location of the project. GPS coordinates inputs and map scrolling are options available in order to determine the projects location as per Figure 30 below.



Name: Hartleyvale WWPS_Try 3

Author: JG Pillay

Description:

MEng Energy : energy profile of 2021 of Hartleyval WWPS is uploaded data from CCT Smart Facility Dash.

Auto seclect (Try 3)

24 Bellevliet Rd, Observatory, Cape Town, 7925, South Africa (33°56.3'S , 18

33° 56' 17.54" S 18° 28' 3

(UTC+02:00) Harare, Pretoria

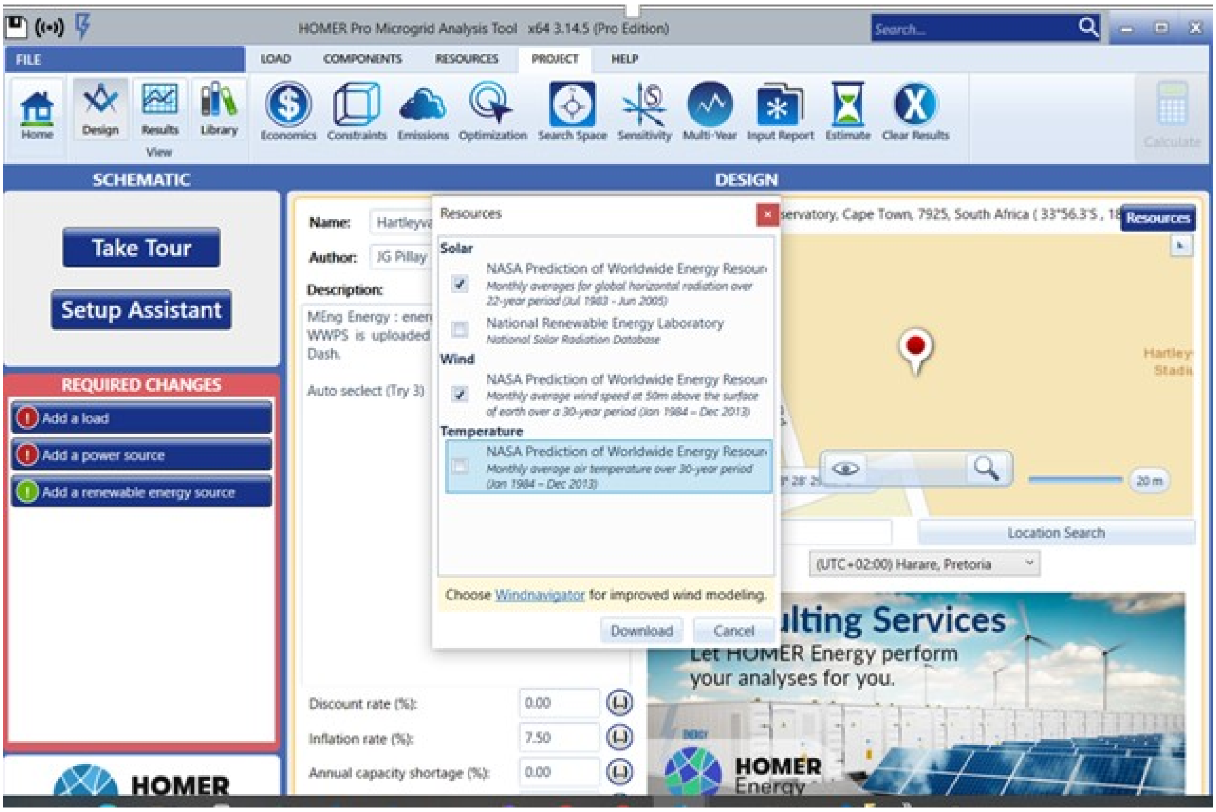
Discount rate (%): 0.00

Inflation rate (%): 7.50

Annual capacity shortage (%): 0.00

Figure 30: Example of search location tab

The ‘resources tab’, located above the ‘search location map’ tab enables the user to select and upload meteorology databases to which the RES for modelled against. This automatically historical data for the site-specific area e.g. solar irradiance, wind speeds etc. and frequencies as per Figure 31 below.



HOMER Pro Microgrid Analysis Tool x64 3.14.5 (Pro Edition)

Name: Hartleyva

Author: JG Pillay

Description:

MEng Energy : ener
WWPS is uploaded
Dash.

Auto seclect (Try 3)

Resources

Solar

☑ NASA Prediction of Worldwide Energy Resourc
Monthly averages for global horizontal radiation over 22-year period (Jul 1983 - Jun 2005)

☐ National Renewable Energy Laboratory
National Solar Radiation Database

Wind

☑ NASA Prediction of Worldwide Energy Resourc
Monthly average wind speed at 50m above the surface of earth over a 30-year period (Jan 1984 – Dec 2013)

Temperature

☐ NASA Prediction of Worldwide Energy Resourc
Monthly average air temperature over 30-year period (Jan 1984 – Dec 2013)

Choose Windnavigator for improved wind modeling.

Discount rate (%): 0.00

Inflation rate (%): 7.50

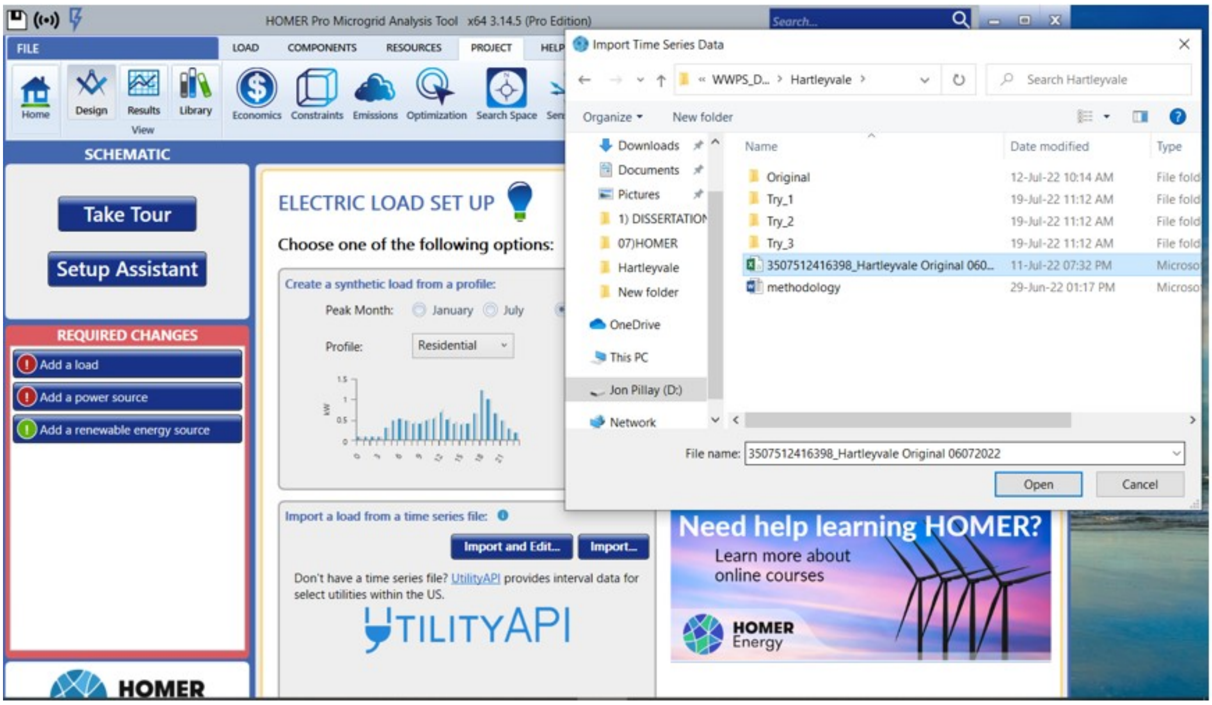
Annual capacity shortage (%): 0.00

servatory, Cape Town, 7925, South Africa (33°56.3'S , 18

(UTC+02:00) Harare, Pretoria

Figure 31: Example of meteorology database tab

HOMER also allows the user to ‘import and edit’ energy load profiles from Excel and CSV format files under the ‘electrical load set up tab’ into the project for simulation as per the Figure 32 below.



ELECTRIC LOAD SET UP

Choose one of the following options:

Create a synthetic load from a profile:

Import a load from a time series file:

Don't have a time series file? UtilityAPI provides interval data for select utilities within the US.

File name: 3507512416398_Hartleyvale Original 06072022

Need help learning HOMER? Learn more about online courses

Figure 32: Example of imported energy load profiles to HOMER

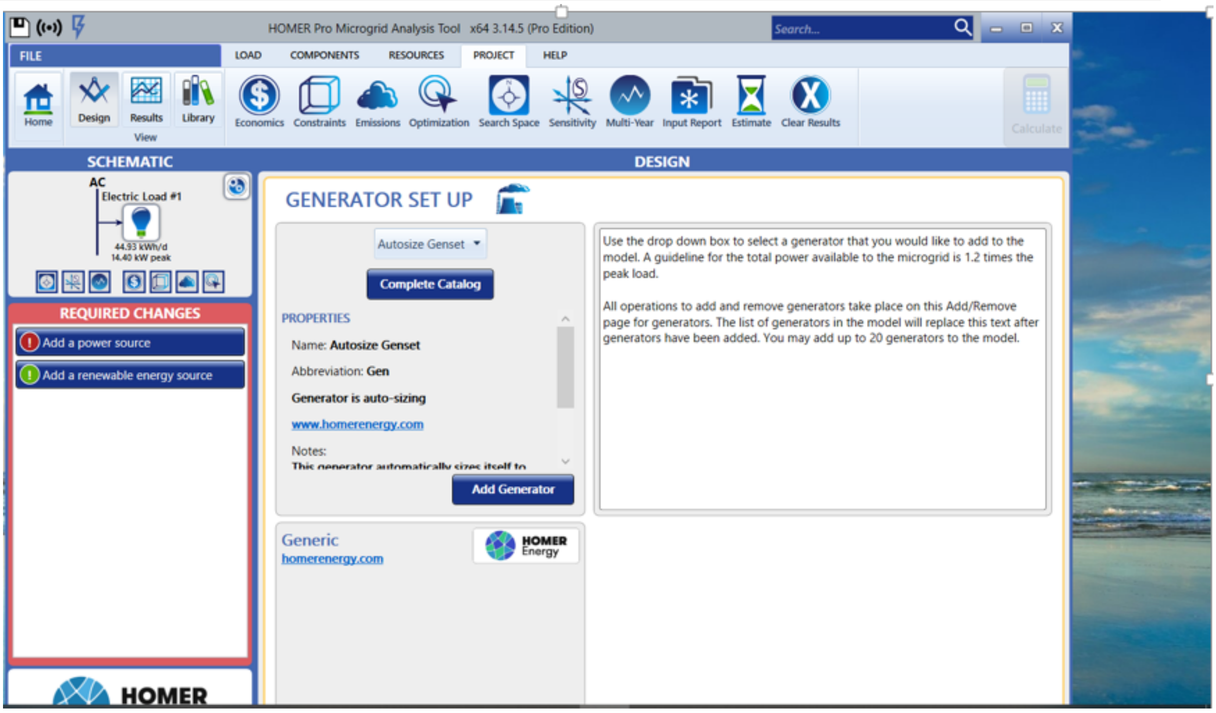
HOMER requires that modelling components be priced individually in-order to run its simulations and select the most feasible RES model. The pricing in Table 12 below was obtained from researchers utilizing HOMER towards case studies. These prices was adapted Dollar to Rand value from that year to 2022. All three case studies will utilized the same input sensitivity variables for the simulations. Table 12 below is the components modelling costs.

Table 12: Modelling component costs

Modelling Components cost (R)						**Reference**
Component	**Capital**		**Replacement**	**O&M**		
SPV	R 17,500.00	/ 1kW	R 13,125.00	R 962.50	/ year	(Abo-Al-Ez, Elaiw and Xia, 2014)
Batteries	R 22,855.00	/ 1kWh Lead Acid	R 20,562.50	R 2,275.00	/ year	
Diesel generator	R 105,000.00	/ 10 kW	R 87,500.00	R 0.02	/ hour	
Converter/Inverter	R 7,000.00	/ 1kW	R 5,250.00	R -	/ year	
Micro-turbine	R 52,500.00	/ 1kW	R 39,375.00	R 525.00	/ year	(Helal, Ghoneim and Halaby, 2013)

Component prices were estimated 2022 based on references

The modelling components of a generator is included in simulation. The prices are added as per Table 12. Figure 33 below indicates the generators addition; however, auto sized during the simulation.



Name: Autosize Genset

Abbreviation: Gen

Generator is auto-sizing

www.homerenergy.com

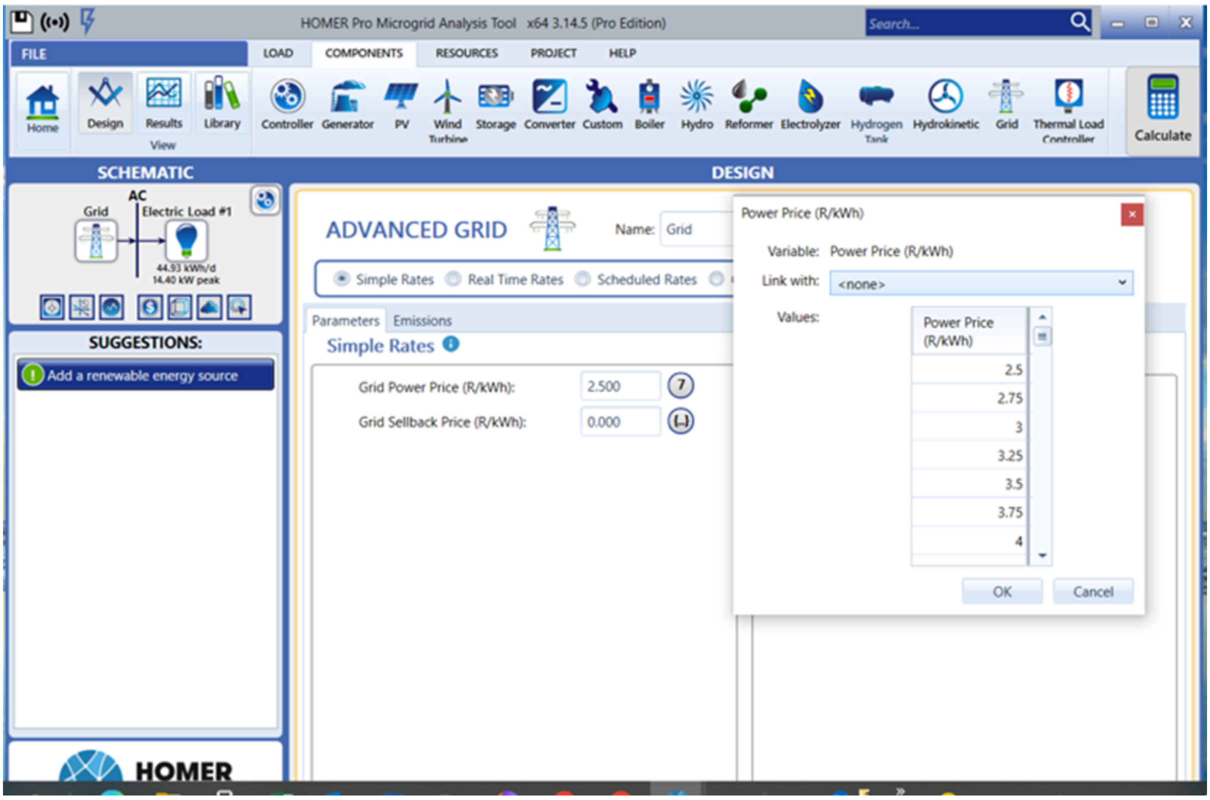
Notes:
This generator automatically sizes itself to

Use the drop down box to select a generator that you would like to add to the model. A guideline for the total power available to the microgrid is 1.2 times the peak load.

All operations to add and remove generators take place on this Add/Remove page for generators. The list of generators in the model will replace this text after generators have been added. You may add up to 20 generators to the model.

Figure 33: Example of input generator and costs tab

The modelling component of grid connection is included in simulation. The prices are of the sensitivity variables in Table 11 were included. Figure 34 below indicates the ‘advance grid’ tab for modelling and simulation.



Name: Grid

Grid Power Price (R/kWh): 2.500

Grid Sellback Price (R/kWh): 0.000

Power Price (R/kWh)

Variable: Power Price (R/kWh)

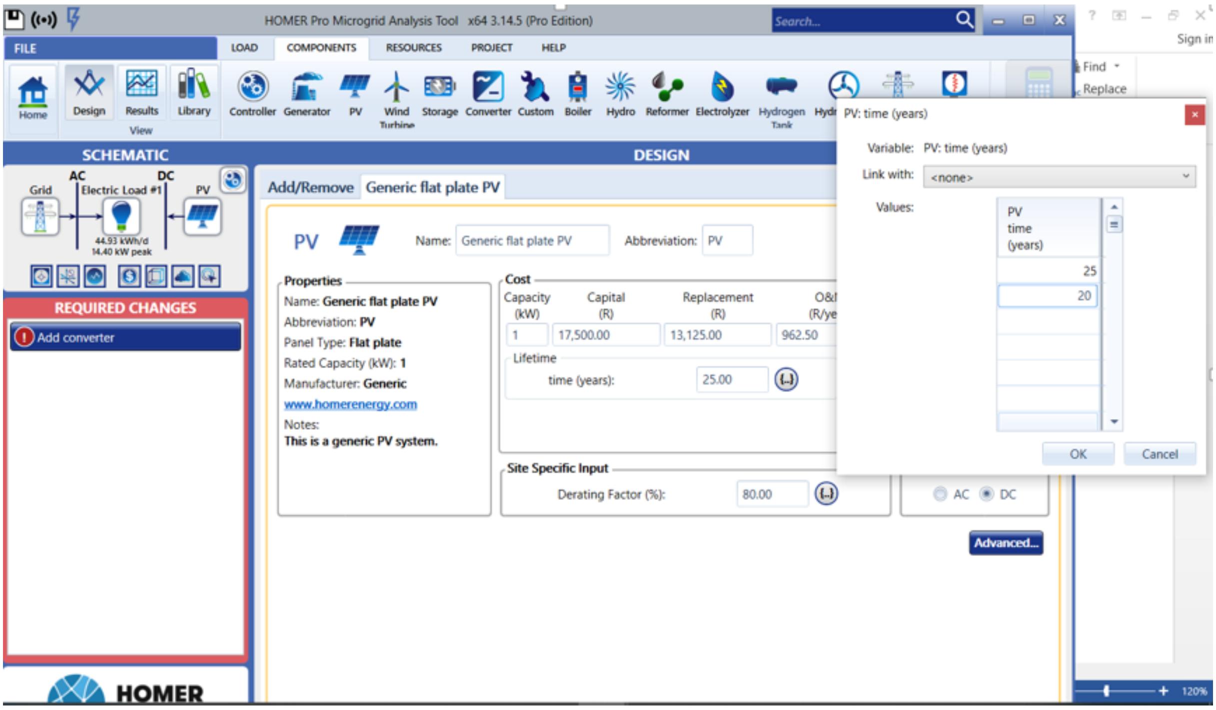
Link with: <none>

Values:

Power Price (R/kWh)
2.5
2.75
3
3.25
3.5
3.75
4

Figure 34: Example of input grid power and tariffs tab

The modelling component of SPV is included in simulation. The prices are added as per Table 12 along with the sensitivity variables in Table 11. Figure 35 below indicates the SPV selection tab, components costs and sensitivity as per Tables 11 and 12.



Name: Generic flat plate PV
Abbreviation: PV

Properties
Name: **Generic flat plate PV**
Abbreviation: **PV**
Panel Type: **Flat plate**
Rated Capacity (kW): **1**
Manufacturer: **Generic**
www.homerenergy.com
Notes:
This is a generic PV system.

Cost

Capacity (kW)	Capital (R)	Replacement (R)	O&M (R/ye
1	17,500.00	13,125.00	962.50

Lifetime
time (years): 25.00

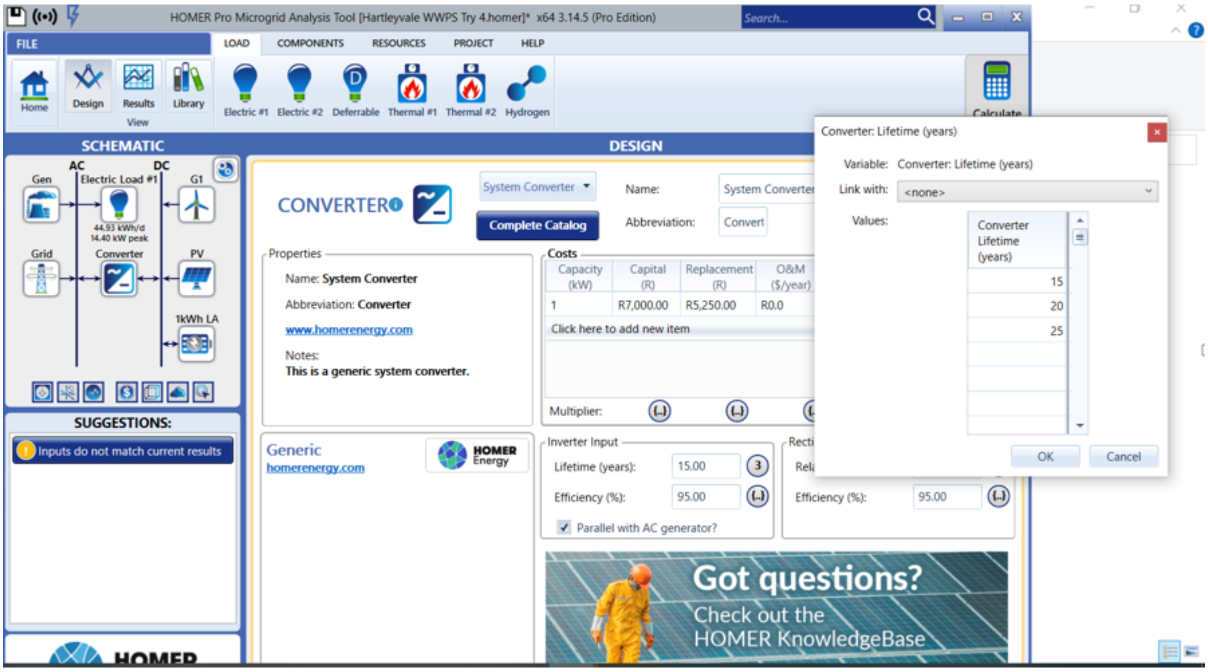
Site Specific Input
Derating Factor (%): 80.00

PV: time (years)
Variable: PV: time (years)
Link with: <none>
Values:

PV time (years)
25
20

Figure 35: Example of input component SPV costs and variables tab

The modelling component of converter is included in simulation in order to aid the SPV. The prices are added as per Table 12 along with the sensitivity variables in Table 11. Figure 36 below indicates the converter selection tab, components costs and sensitivity as per Tables 11 and 12.



Name: System Converter
Abbreviation: Convert

Properties
Name: **System Converter**
Abbreviation: **Converter**
www.homerenergy.com
Notes:
This is a generic system converter.

Costs

Capacity (kW)	Capital (R)	Replacement (R)	O&M ($/year)
1	R7,000.00	R5,250.00	R0.0
Click here to add new item			

Multiplier:

Inverter Input
Lifetime (years): 15.00
Efficiency (%): 95.00
☑ Parallel with AC generator?

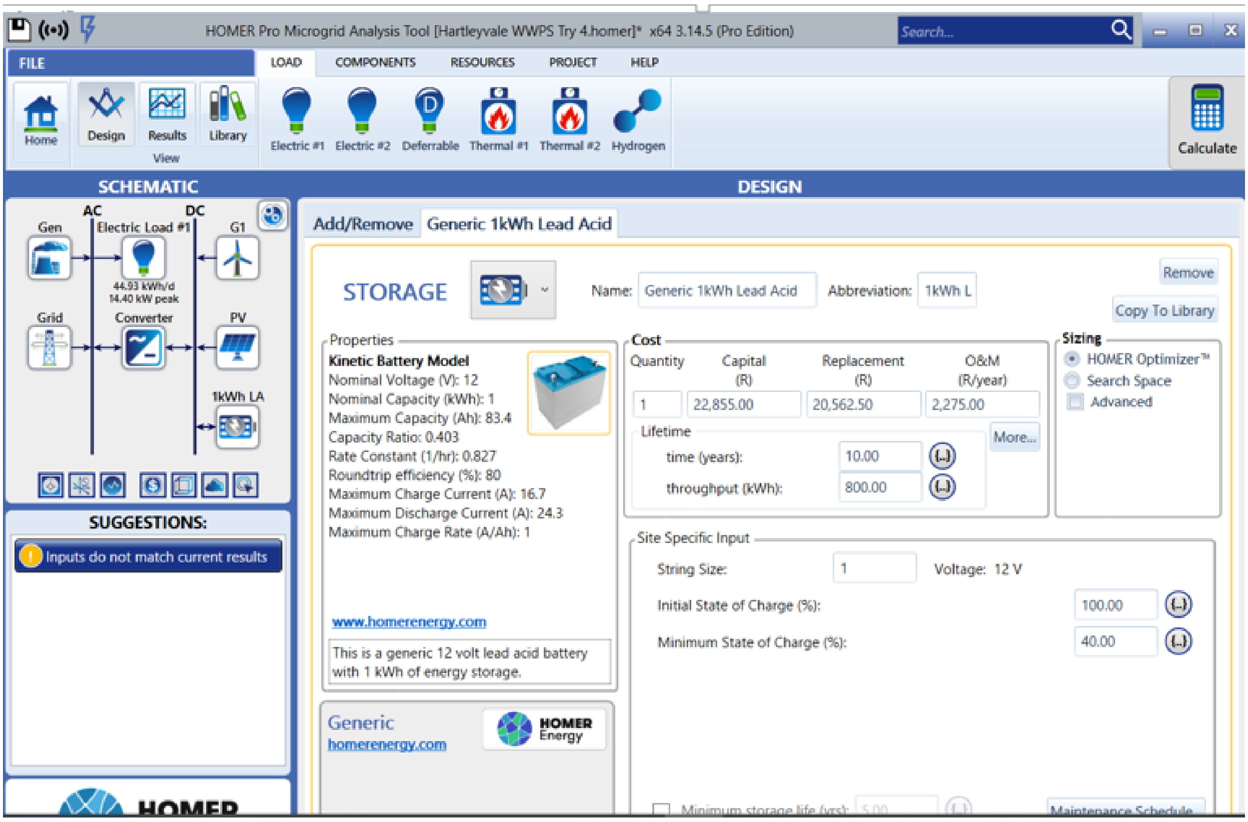
Recti
Efficiency (%): 95.00

Converter: Lifetime (years)
Variable: Converter: Lifetime (years)
Link with: <none>
Values:

Converter Lifetime (years)
15
20
25

Figure 36: Example input converter cost and variables tab

The modelling component of battery storage is included in simulation. The prices are added as per Table 12 along with the sensitivity variables in Table 11. Figure 37 below indicates the ‘storage selection’ tab, components costs and sensitivity as per Tables 11 and 12.



HOMER Pro Microgrid Analysis Tool [Hartleyvale WWPS Try 4.homer]* x64 3.14.5 (Pro Edition)

Inputs do not match current results

Name: Generic 1kWh Lead Acid Abbreviation: 1kWh L

Properties

Kinetic Battery Model
Nominal Voltage (V): 12
Nominal Capacity (kWh): 1
Maximum Capacity (Ah): 83.4
Capacity Ratio: 0.403
Rate Constant (1/hr): 0.827
Roundtrip efficiency (%): 80
Maximum Charge Current (A): 16.7
Maximum Discharge Current (A): 24.3
Maximum Charge Rate (A/Ah): 1

www.homerenergy.com

This is a generic 12 volt lead acid battery with 1 kWh of energy storage.

Cost

Quantity	Capital (R)	Replacement (R)	O&M (R/year)
1	22,855.00	20,562.50	2,275.00

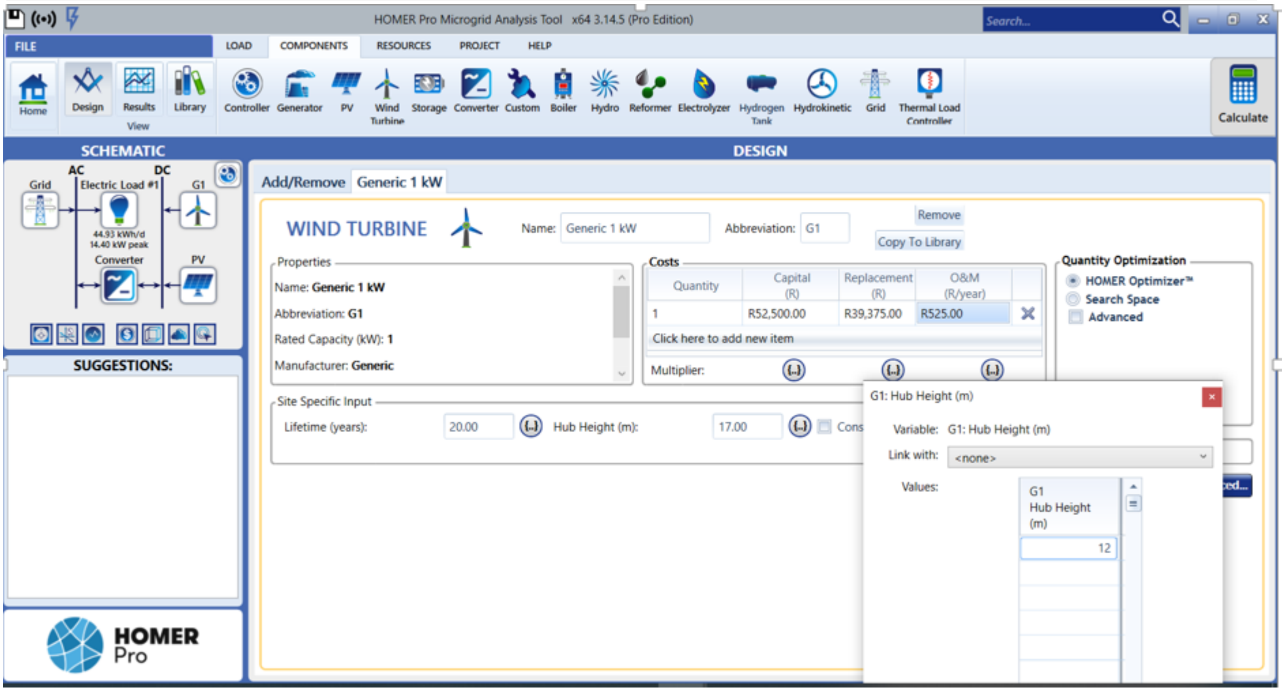
Lifetime
time (years): 10.00
throughput (kWh): 800.00

Sizing
● HOMER Optimizer™
○ Search Space
☐ Advanced

Site Specific Input
String Size: 1 Voltage: 12 V
Initial State of Charge (%): 100.00
Minimum State of Charge (%): 40.00
☐ Minimum storage life (yrs): 5.00

Figure 37: Example of input storage cost and variables tab

The modelling component of wind is included in simulation. The prices are added as per Table 12 along with the sensitivity variables in Table 11. Figure 38 below indicates the ‘wind turbine’ tab, components costs and sensitivity as per Tables 11 and 12.



WIND TURBINE

Name: Generic 1 kW

Abbreviation: G1

Properties

Name: **Generic 1 kW**

Abbreviation: **G1**

Rated Capacity (kW): **1**

Manufacturer: **Generic**

Costs

Quantity	Capital (R)	Replacement (R)	O&M (R/year)
1	R52,500.00	R39,375.00	R525.00

Site Specific Input

Lifetime (years): 20.00

Hub Height (m): 17.00

Quantity Optimization

● HOMER Optimizer™

○ Search Space

☐ Advanced

G1: Hub Height (m)

Variable: G1: Hub Height (m)

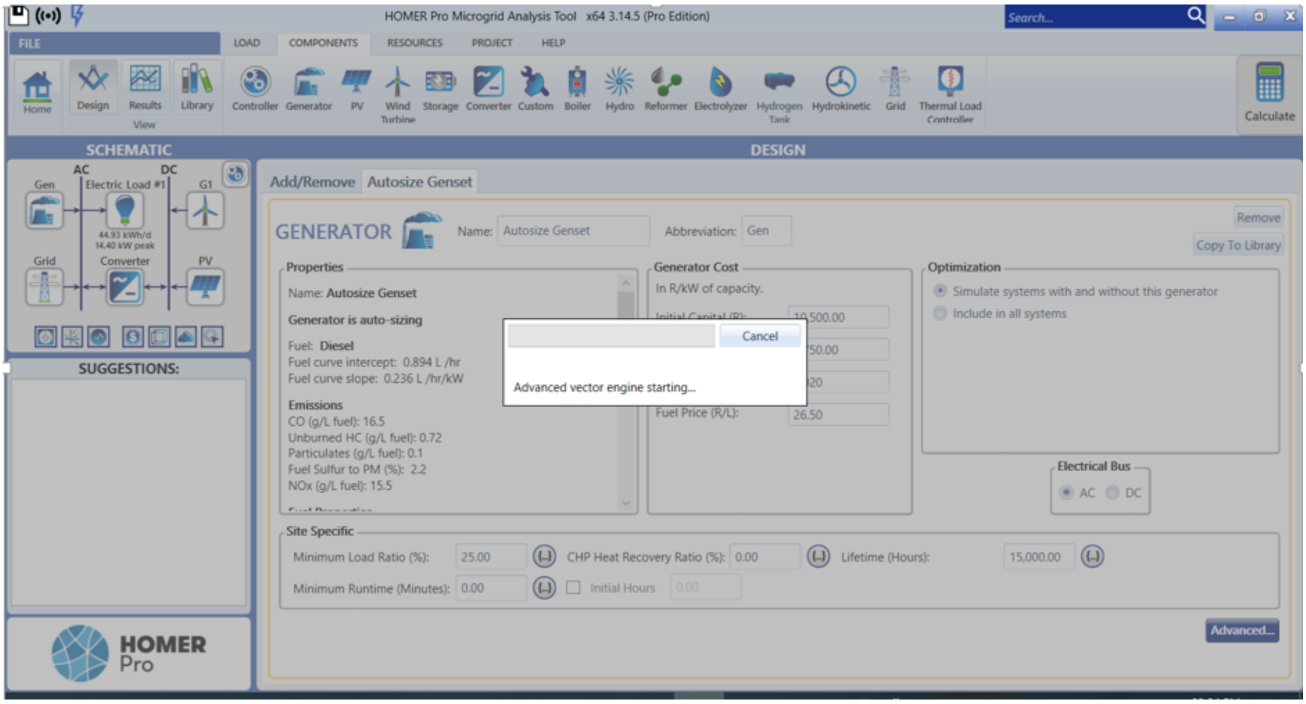
Link with: <none>

Values:

G1 Hub Height (m)
12

Figure 38: Example of Inputs wind cost and variables tab

We then complete the selection of modelling components and select the ‘calculate’ tab. This process is done by following all the steps for each case study. Figure 39 below displays the calculations taking place.



GENERATOR

Name: Autosize Genset

Abbreviation: Gen

Properties

Name: Autosize Genset

Generator is auto-sizing

Fuel: Diesel

Fuel curve intercept: 0.894 L/hr

Fuel curve slope: 0.236 L/hr/kW

Emissions

CO (g/L fuel): 16.5

Unburned HC (g/L fuel): 0.72

Particulates (g/L fuel): 0.1

Fuel Sulfur to PM (%): 2.2

NOx (g/L fuel): 15.5

Generator Cost

In R/kW of capacity.

Fuel Price (R/L): 26.50

Cancel

Advanced vector engine starting...

Optimization

● Simulate systems with and without this generator

○ Include in all systems

Electrical Bus

● AC ○ DC

Site Specific

Minimum Load Ratio (%): 25.00

CHP Heat Recovery Ratio (%): 0.00

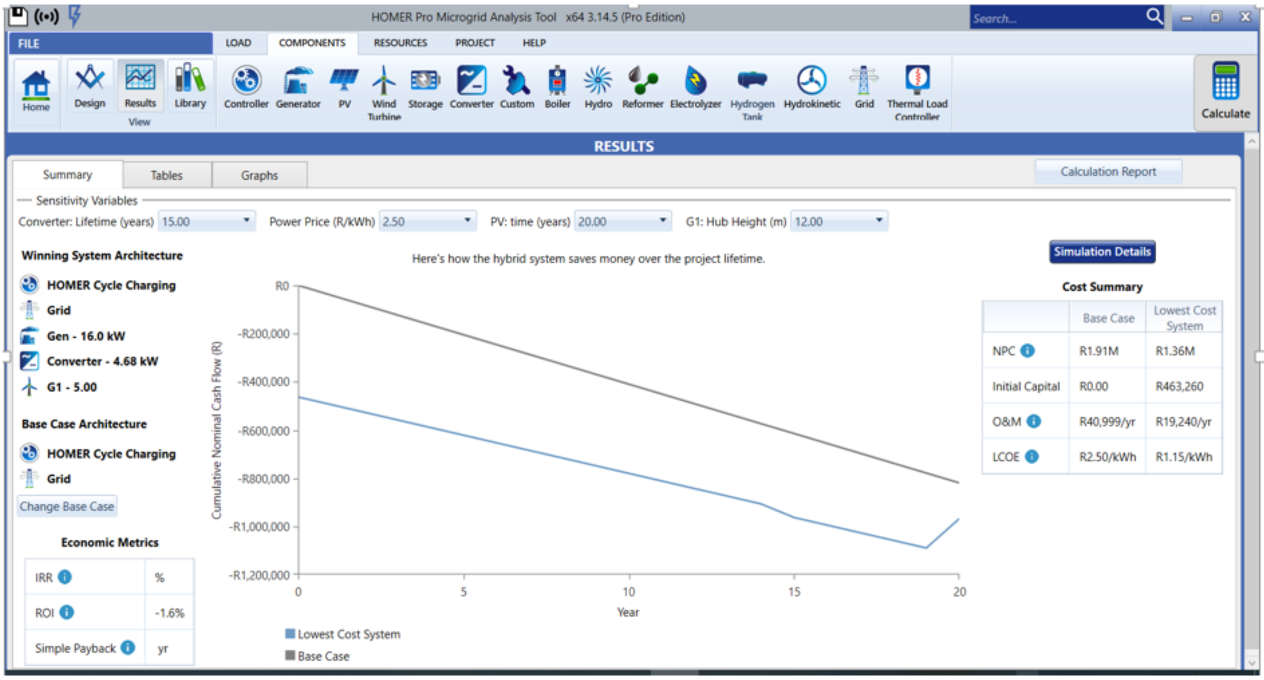
Lifetime (Hours): 15,000.00

Minimum Runtime (Minutes): 0.00

☐ Initial Hours 0.00

Figure 39: Example of simulating scenarios

The simulation outputs are indicated by a graph of the feasibility of the best-suited option as per Figure 40 below.



Sensitivity Variables

Converter: Lifetime (years) 15.00

Power Price (R/kWh) 2.50

PV: time (years) 20.00

G1: Hub Height (m) 12.00

Winning System Architecture

HOMER Cycle Charging

Grid

Gen - 16.0 kW

Converter - 4.68 kW

G1 - 5.00

Base Case Architecture

HOMER Cycle Charging

Grid

Here's how the hybrid system saves money over the project lifetime.

Economic Metrics

IRR	%
ROI	-1.6%
Simple Payback	yr

Cost Summary

	Base Case	Lowest Cost System
NPC	R1.91M	R1.36M
Initial Capital	R0.00	R463,260
O&M	R40,999/yr	R19,240/yr
LCOE	R2.50/kWh	R1.15/kWh

Figure 40: Example of summary of the simulation

4.6 HOMER modelling schematic design

The HOMER schematic design stems from the components one has selected in order to run the simulation along with the sensitively variables. In all three cases, this would also indicate the calculated electrical load and well as the peak power consumption.

4.6.1 HOMER modelling Royal Road WWPS schematic design

Figure 41 below shows the selected RE components for Royal Road WWPS simulation. The proposed schematic shows that the electrical load calculated at 133.97 kWh/ day with a 42.24 kW peak.

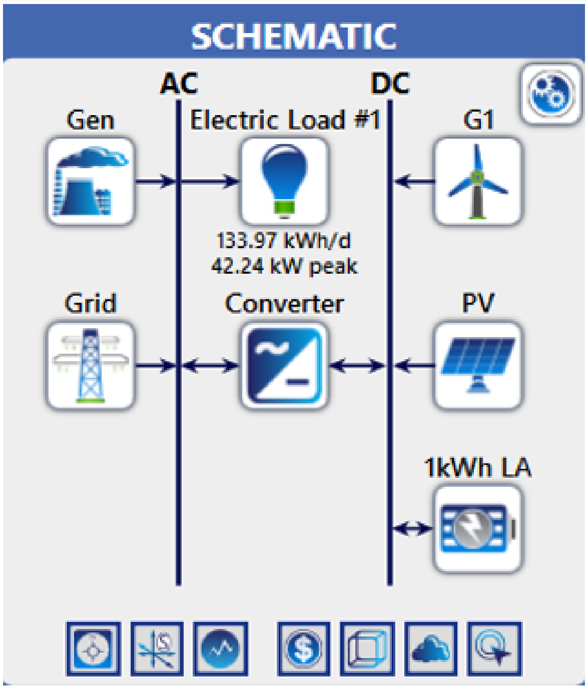


Figure 41: Initial proposed schematic design for Royal Road WWPS

4.6.2 HOMER modelling Parade Chalets WWPS schematic design

Figure 42 below shows the selected RE components for Parade Chalets WWPS simulation. The proposed schematic shows that the electrical load calculated at 65.92 kWh/day with a 5.80 kW peak.

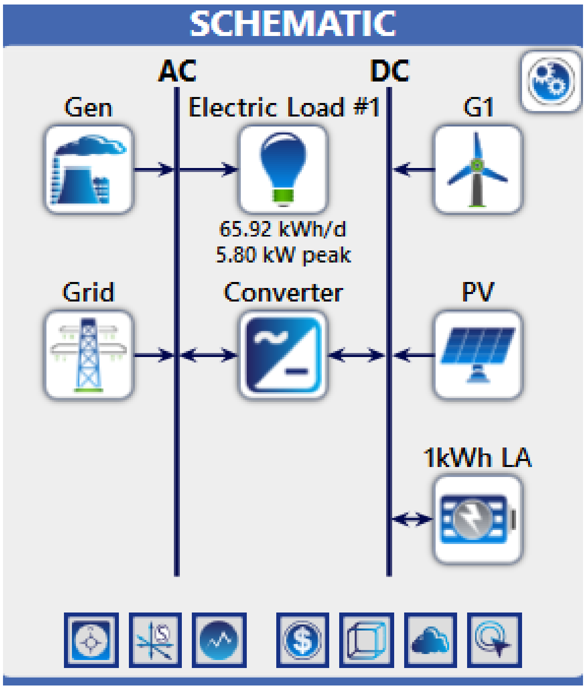


Figure 42: Initial proposed schematic design for Parade Chalets WWPS

4.6.3 HOMER modelling Hartleyvale WWPS schematic design

Figure 43 below shows the selected RE components for the Hartleyvale WWPS simulation. The proposed schematic shows that the electrical load calculated at 44.93 kWh/day with a 14.4 kW peak.

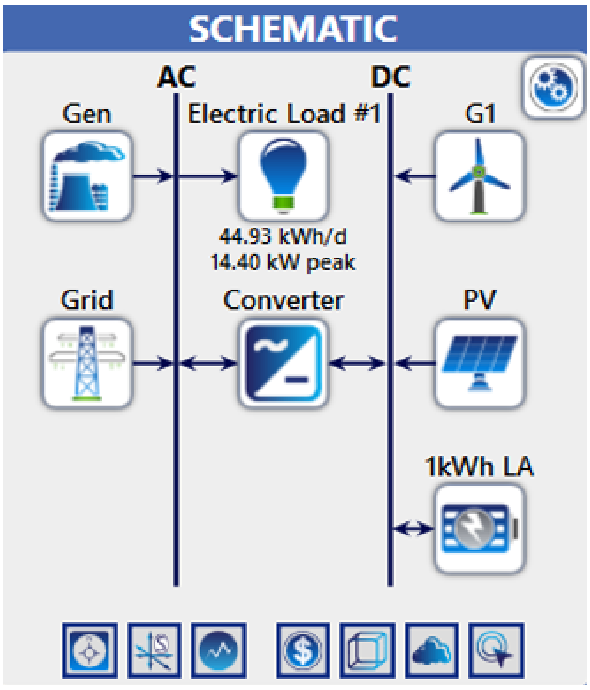


Figure 43: Initial proposed schematic design for Hartleyvale WWPS

CHAPTER 5: RESULTS AND DISCUSSION

PART 3: RESULTS AND DISCUSSION OF WASTEWATER ENERGY BENCHMARKING

5.1 Energy benchmarking of Cape Town’s wastewater pumping stations

This portion of the study shows the results of the energy benchmarking along with the discussion.

5.1.1 WWPS data results for Wood Drive WWPS

The results of the normalization and statistical study are shown and discussed here. The results of the normalization study shows the mean values and standard deviation. A graphical representation of the results of the data collected for: 1) flow vs time; 2) energy consumption vs time and 3) energy intensity is shown as part of the statistical study.

5.1.1.1 Wood Drive WWPS inflow data results

The Ecograph T RSG35 Universal Data Manager delivered the flow data for Wood Drive WWPS from 01 January 2021 up until the 31 December 2021 as shown in the Figure 48 below. From figure 40 below, we can see that from the months of January till December 2021 the sewage flows are constant for most of the year ranging between 380 till 390 m³/ day. There are six distinct valleys in the data around the January, March September and November 2021 where the inflow supposedly drops to 0.0 m³/day. The mean of the flow data was calculated to be 369 m³/ day with a standard deviation of 65.2.

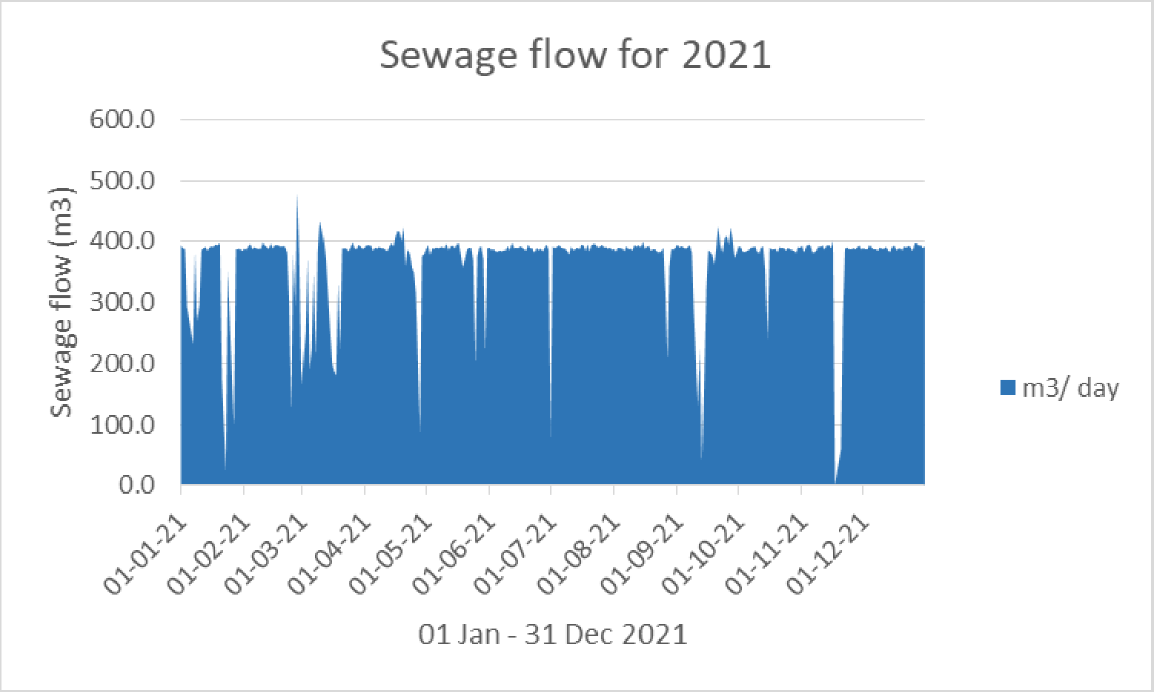


Figure 44: Daily inflow from Wood Drive WWPS (2021)

5.1.1.2 Wood Drive WWPS inflow data discussion

The Wood Drive WWPS sewage flows shows a constant daily inflow of between 370 m³ to 390 m³. The six valleys indicated in the in the months of January; March; September and November 2021 are months where fault reading had occurred within the PS. These fault readings was provided in the data extraction of the Ecograph T RSG35 Universal Data Manager when the data was collected on site. The dates for these faults were 05 to 06 January; 22 January; 02 to 03 March; 10 September and 18 to 19 November respectively. The faults logged on these days resulted in a 0.00 m³/ day and are indicated in Figure 44.

5.1.1.3 Wood Drive WWPS energy data results

The Landis Gyr AMR energy recorder had provided comprehensive energy consumption data for Wood Drive WWPS for the year 2021 as per Figure 45 below.

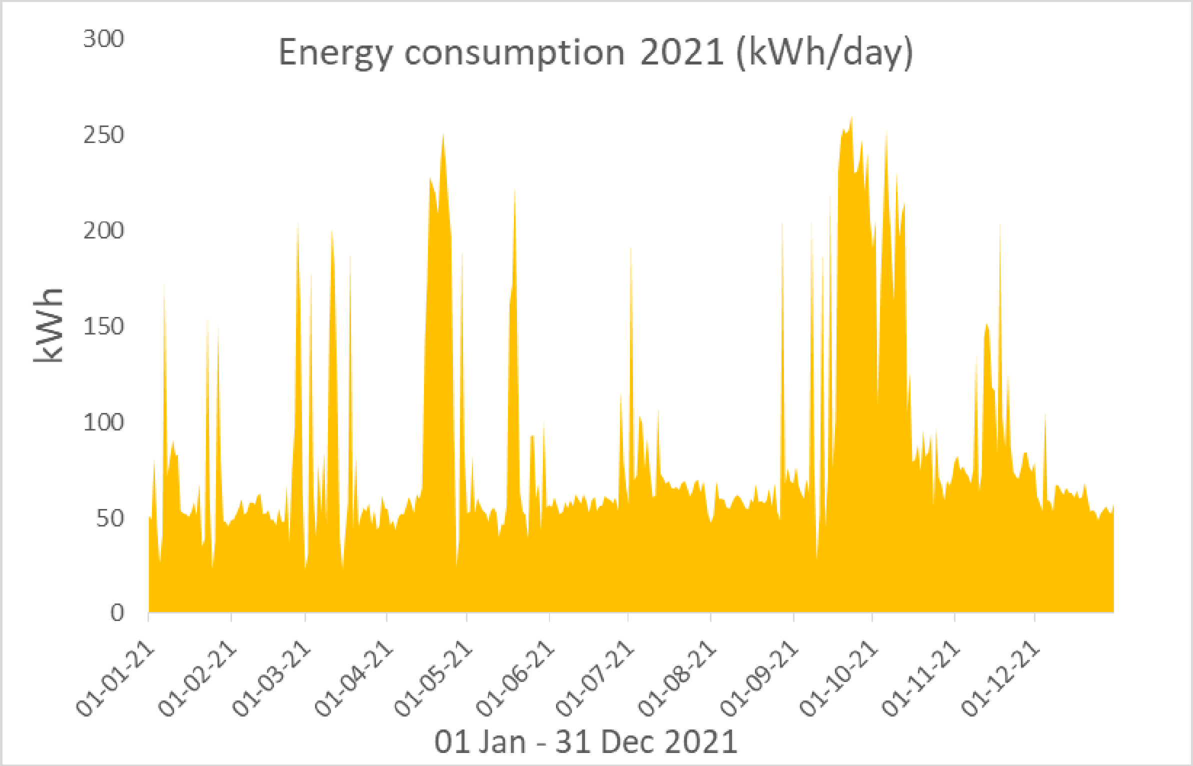


Figure 45: Energy consumption of Wood Drive WWPS (2021)

From Figure 45 above, we observe 20 peaks in energy consumption which throughout the year, all occurring between January and December 2021, which are all above 100 kWh/ day. Where five peaks are occurring between May until October 2021 and the where the energy usage is in excess of 200 kWh/ day. Furthermore, we observe that the average daily energy consumption ranges between 40 - 50 kWh/day consistently throughout the year. It should also be noted that there are five distinct drops in energy consumption below the 30 kWh/day in the months of January; March and September 2021 however. The mean of the energy consumption data was calculated to be 87.6 kWh/ day with a standard deviation of 55.8.

5.1.1.4 WWPS energy data discussion

From Figure 45 above, we observe 20 distinct energy consumption peaks, which occur between the months of January until November 2021. Peak wet weather flow, stemming from ground water pipe infiltration as a result of storms was thought to be the cause however, this cannot be the case as there are no spikes in the flow data of Figure 44. The spike in energy consumption could most likely be due the air-conditioning inside the facility used to cool the motor control centre (MCC) boards, but this is purely speculation.

5.1.2 WWPS specific energy intensity vs time results

The results of the statistical study, conducted via Excel, was done in order to graphically to establish the correlation between the variable data sets of flow (m³/day) and energy consumption (kWh/day). The study simply matched the dates of the time periods for energy consumption against the flow volume. The specific energy consumption for that day is shown for the year 2021 in Figure 46 below.

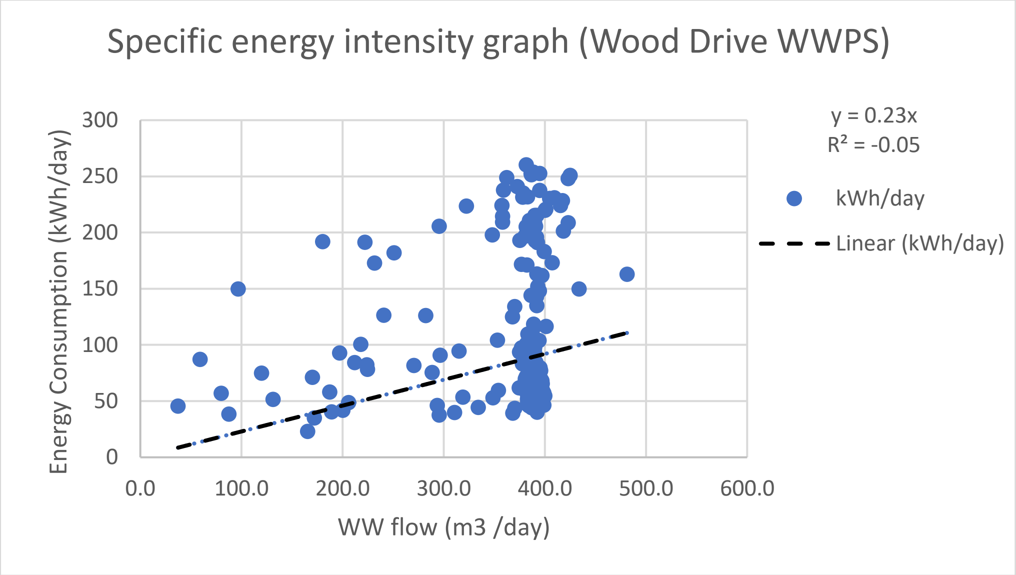


Figure 46: Energy against flow data for Wood Drive WWPS (2021)

By correlating the daily energy consumption plotted against the daily flow data we can see the relationship between these two variables at Wood Drive WWPS as per Figure 21. When the graph of Figure 46 is read from left to right, there is an ‘increasing trend’ in the function where y = 0.23x. The data correlation is approximately linear as these points are following a straight-line pattern. The strength of the correlation tends towards a ‘fairly strong/ moderate’ association due to the fact that there is a fair amount of ‘scatter’ correlation on the upward and downwards end of the trend line. The Pearson’s correlation coefficient of $R^2 = -0.05$, confirms that the data points towards a ‘moderate’ association of correlation. Figure 46 tends to indicate that a flow of around 390 to 400.0m³ can have an energy expenditure between 40 to 250 kWh /day as a majority grouping is located along this mark.

5.1.3 WWPS specific energy intensity discussion

The average of the specific energy consumption of Wood Drive WWPS was calculated to be 0.252 kWh/ m³ with a standard deviation of 0.197 and the median calculated at 0.167, which is similar to the energy intensity levels of WWP recorded in India and New Zealand in Table 5. Several correction data points where the flow reading was 0.0m³ /

day where omitted from this graph as this points would probably skew the trend line. The flow data point omitted totalled 10 and there associating energy consumption varied between 25kWh/day to over 200 kWh/ day. The flow data for those days were logged as a fault (0.00 m^3/day) and a report was also generated upon the data being extracted. Pillay, (2021) found a fair amount of grouping occurred between the 300.0 to 500.0 m^3 for Wood Drive WWPS in a shorter 22 day study in 2019, with an energy consumption ranging between 20 kWh to 150kWh/ day. This observation is also made where such a grouping is found in Figure 46 of this study as well. There is a fair amount of scatter on the data, however an R^2 value of -0.05 does not necessarily indicate that exercise was futile, but an indication of a measure of strength and direction between variable. One could therefore say that to pump around of 400.0 m^3/ day would likely result in varied energy consumption; however, one should also note that statistics are a guide subjected to an infinite amount of variables.

PART 4: RESULTS AND DISCUSSION OF MATHEMATICAL SOFTWARE MODELLING FOR WWPSs RE SYSTEMS

5.2 Results and discussion of HOMER simulation Royal Road WWPSs

5.2.1 Results of Royal Road WWPS energy profile

The results of the energy loading profile for Royal Road WWPS is indicated in Figures 47, 48 and 49 below. Figures 47 and 48 was obtained directly from SFD. The data of Royal Road WWPS year 2021 was fed in to Excel with Figure 49 as the result. This energy load profile was uploaded directly into HOMER for the modelling simulation of RESs.

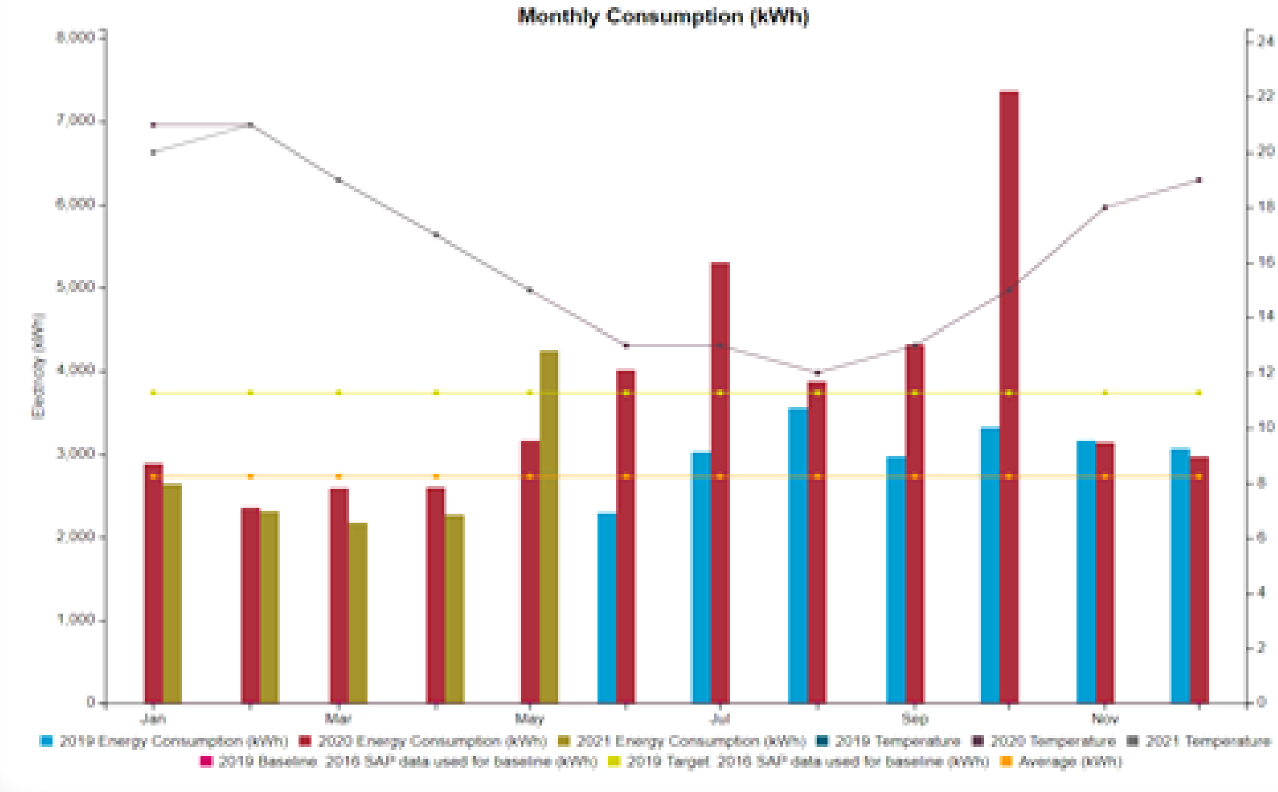


Figure 47: Yearly energy consumption for Royal Road WWPS obtained from SFD

The monthly energy consumption profile for the years 2019, 2020 and 2021 are shown in Figure 47 above. The figure shows that the energy consumption data monitoring commenced in June 2019 and shows that data collection had stopped in May 2021 for Royal Road WWPS.

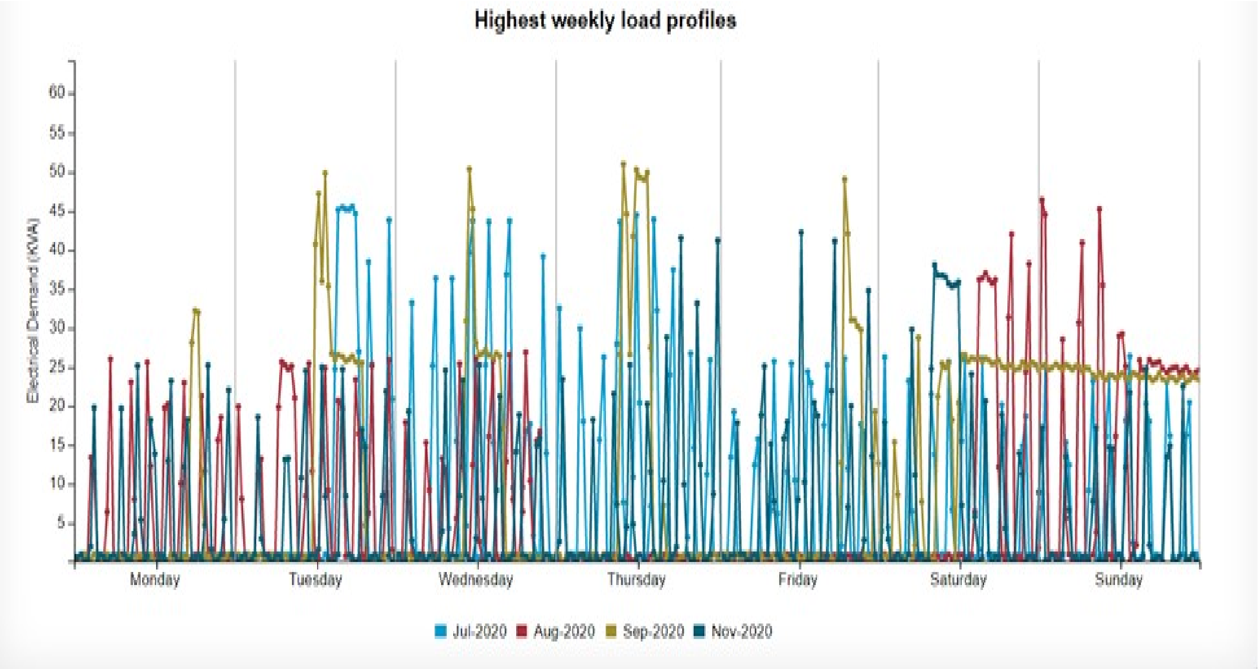


Figure 48: Highest recorded weekly energy load profile for Royal Road WWPS obtained from SFD

The highest weekly electrical demand profile (kVA) for the months of July, August, September and November 2020 is shown in Figure 48. The figure was obtained directly from SFD and shows that the electrical demand was the highest in those four weeks since the data monitoring commenced.

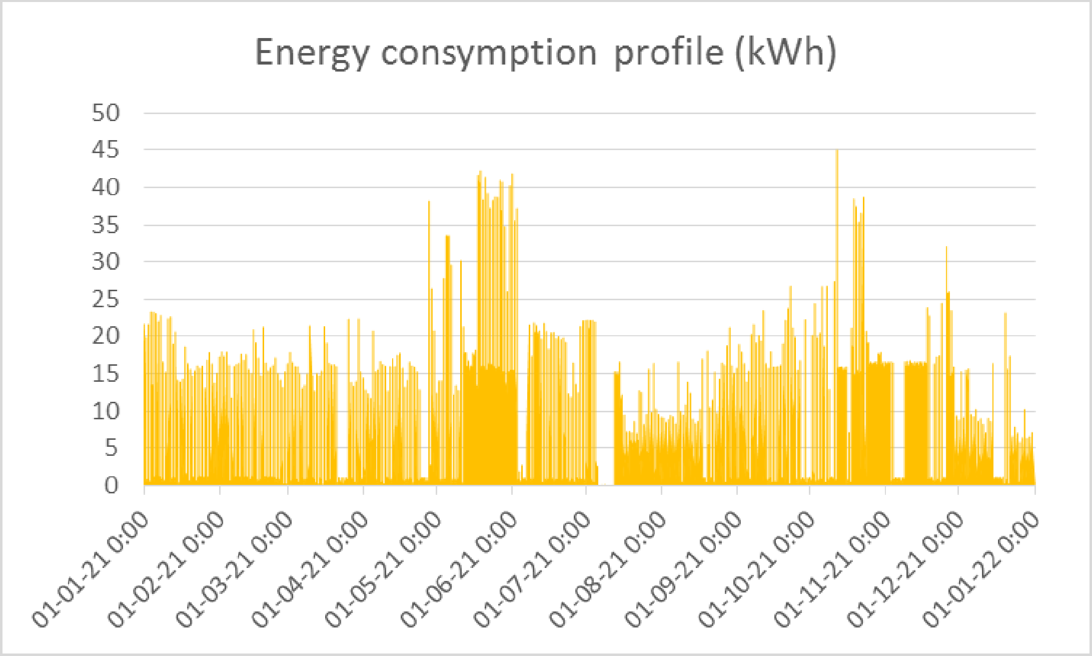
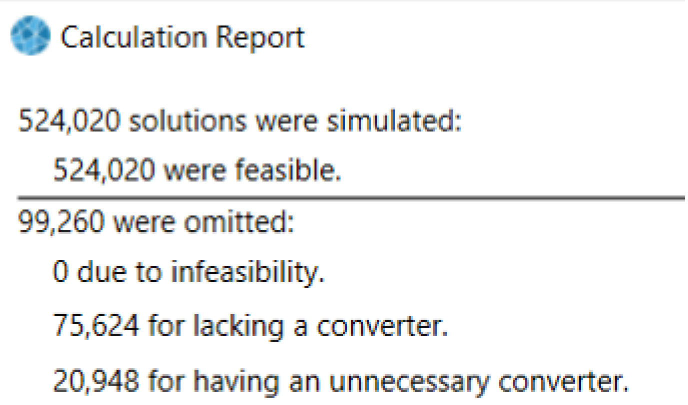


Figure 49: Energy consumption of Royal Road WWPS for year 2021 obtained from SFD (Excel)

From Figure 49 above, we observe eight distinct groupings in energy consumption which throughout the year in excess of 25 kWh, all occurring between May and November 2021. Where six peaks and groupings are occurring between June until November 2021. One drop in energy consumption can be observed around late July till early August 2021 with the consumption being 0.0 kWh. Nevertheless, the energy consumption is show constantly ranging between 1.0 kWh to between 15 to 20 kWh daily.

5.2.2 Results of HOMER simulation for Royal Road WWPS

Figure 50 below indicates that 524 020 solutions were simulated of which 99 260 were omitted, 75 624 omitted due to lacking a converter and 20 948 omitted for having a converter unnecessarily.



Calculation Report

524,020 solutions were simulated:

524,020 were feasible.

99,260 were omitted:

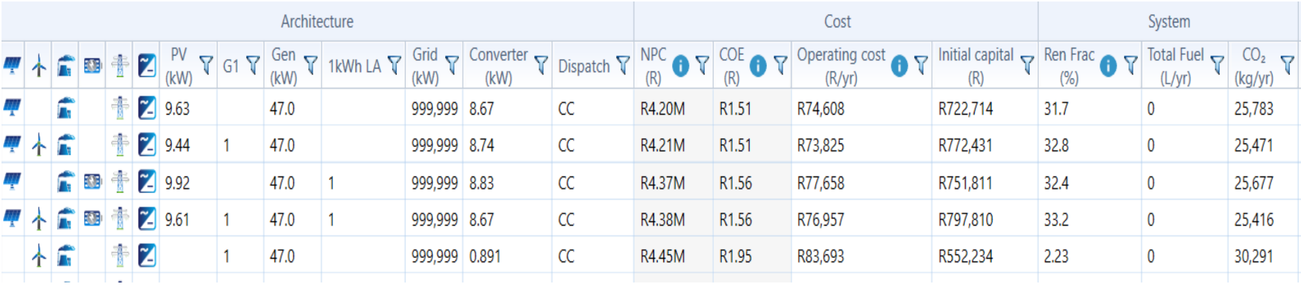
0 due to infeasibility.

75,624 for lacking a converter.

20,948 for having an unnecessary converter.

Figure 50: Simulated solutions for Royal Road WWPS

Figure 51 below indicates the top five optimization results for Royal Road WWPS. Of the top five, four results indicate the inclusion of SPV and three the inclusion of wind turbine where the cost of energy (COE) ranges between R1.51 – R1.95 / kWh.



Architecture													Cost				System		
						PV (kW)	G1	Gen (kW)	1kWh LA	Grid (kW)	Converter (kW)	Dispatch	NPC (R)	COE (R)	Operating cost (R/yr)	Initial capital (R)	Ren Frac (%)	Total Fuel (L/yr)	CO₂ (kg/yr)
●		●		●	●	9.63		47.0		999,999	8.67	CC	R4.20M	R1.51	R74,608	R722,714	31.7	0	25,783
●	●	●		●	●	9.44	1	47.0		999,999	8.74	CC	R4.21M	R1.51	R73,825	R772,431	32.8	0	25,471
●		●	●	●	●	9.92		47.0	1	999,999	8.83	CC	R4.37M	R1.56	R77,658	R751,811	32.4	0	25,677
●	●	●	●	●	●	9.61	1	47.0	1	999,999	8.67	CC	R4.38M	R1.56	R76,957	R797,810	33.2	0	25,416
	●	●		●	●		1	47.0		999,999	0.891	CC	R4.45M	R1.95	R83,693	R552,234	2.23	0	30,291

Figure 51: Optimization results for Royal Road WWPS

Figure 52 below indicates the optimized proposal of adding 9.6 kW of SPV and 47 kW of generator capacity in order to reduce operating costs to R74 608.00 / year.

Figure 52: Proposed RE system for Royal Road WWPS

Figure 53 below indicates the simple payback of the proposed system at 11.2 years of the 15-year. The system's operating costs to R48 428.00 / year with an annualized saving of R73 821.00/ year. Emissions span with carbon emissions decreasing to 25.783 tCO2e/ year opposed to 30.904 tCO2e/ year with grid energy. The proposed system also indicates a drop in cash flow at 14 years and this is likely due to the salvage costs recuperated back into the cashflow.

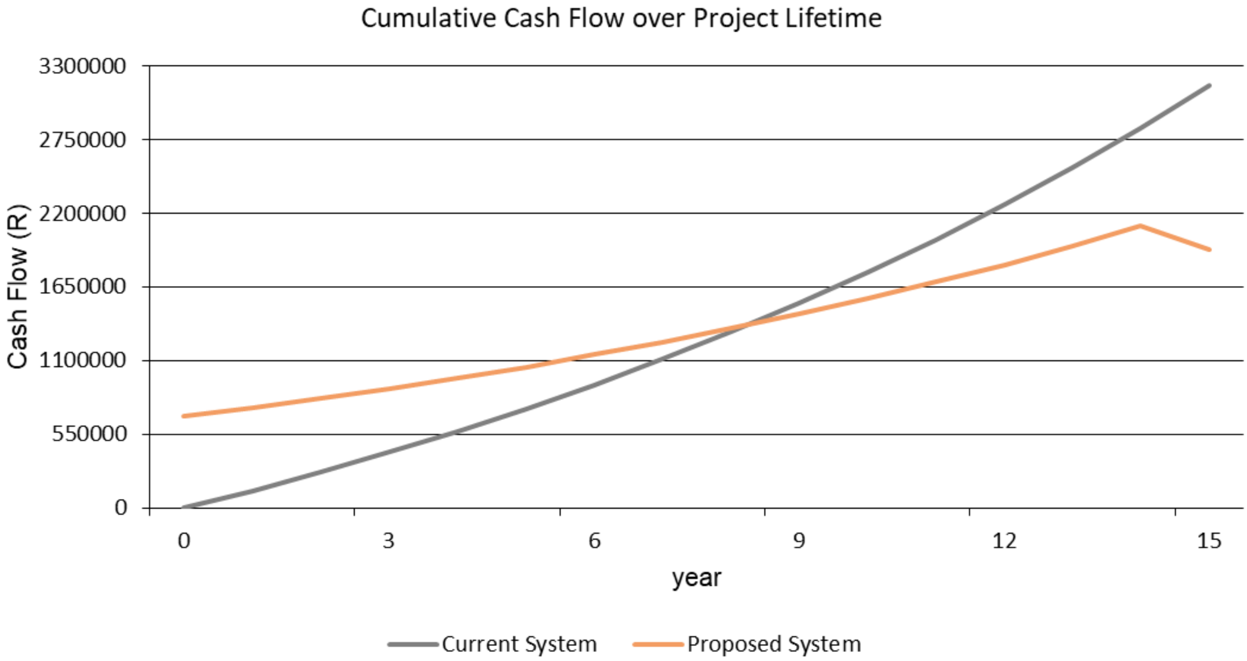


Figure 53: Feasibility summary

5.2.3 Discussion of Royal Road WWPS energy profile

Figure 47 indicated the monthly energy consumption profile for the years 2019, 2020 and 2021, which was directly obtained from the FSD. The figure shows that the energy consumption data monitoring had stopped in May 2021, however the data located under folder was up to June 2022. This could mean that these profiles were not automatically updated. From Figure 49 we observe eight distinct groupings in energy consumption which throughout the year in excess of 25 kWh, all occurring between in the winter months of May until November 2021. One could assume that the spikes in consumption was due to increasing pipe infiltration during the winter season. The drop in energy consumption around late July / early August 2021 could likely be attributed to the PS being inactive, due to a maintenance issue with the consumption being 0.0 kWh.

5.2.4 Discussion of HOMER simulation Royal Road WWPS

Figure 52 indicates the feasibility of the proposed RES (SPV; converter; diesel generator and grid energy), however the results simulated that the simple buy-back would take around 11 years which differs from the graphs graphical display. This could be a fault in HOMER when generating the graph. The Initial proposed schematic design for Royal Road WWPS, as seen in Figure 41, resulted in the 4th best option with a COE resulting in R1.56/kWh, however the HOMER simulations had revealed more suitable and cheaper options, which resulted in Figure 52 RES proposal. Overall a decrease in cost and GHGs can be observed.

5.3 Results and discussion of HOMER simulation Parade Chalets WWPSs

5.3.1 Results Parade Chalets WWPS energy profile

The results of the energy loading profile for Parade Chalets WWPS is indicated in Figures 54, 55 and 56 below. Figures 54 and 55 was obtained directly from SFD. The data of Parade Chalets WWPS year 2021 was fed in to Excel with Figure 56 as the result. This energy load profile was uploaded directly into HOMER for the modelling simulation of RESs.

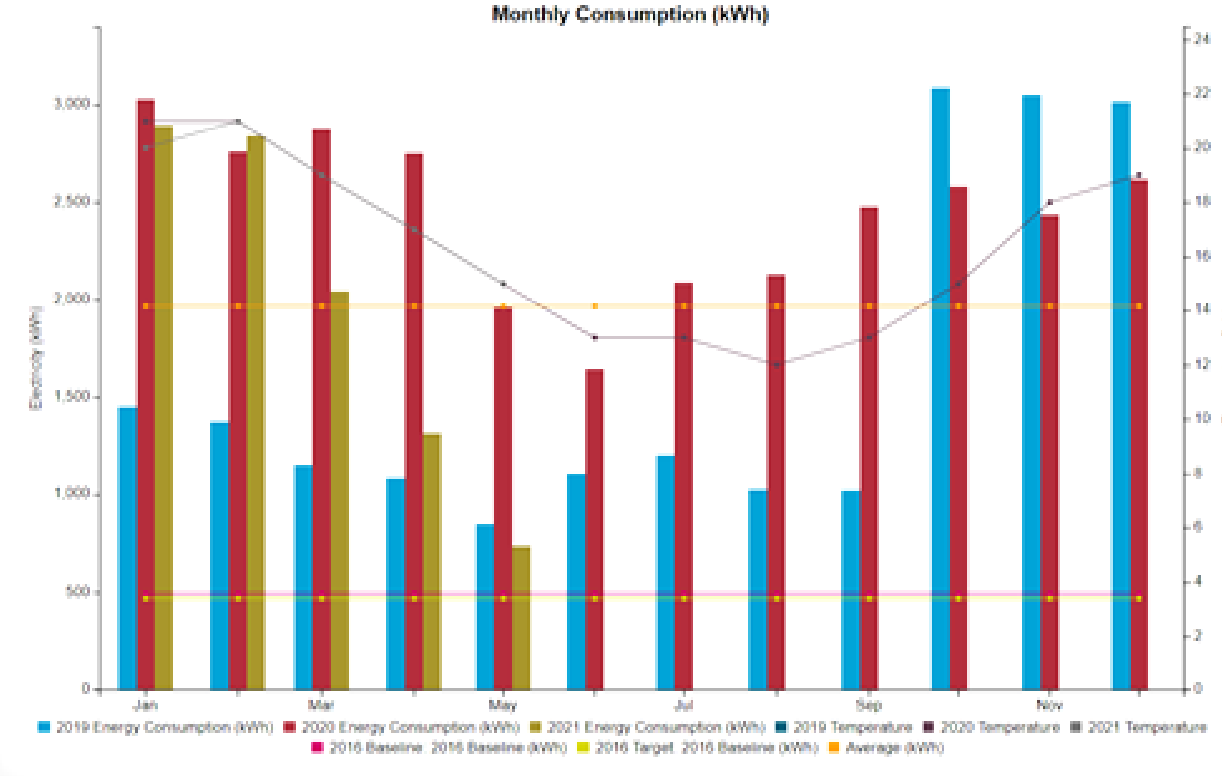


Figure 54: Yearly energy consumption for Parade Chalets WWPS

The monthly energy consumption profile for the years 2019, 2020 and 2021 are shown in Figure 54 for Parade Chalets WWPS. Figure 59 shows that the energy consumption data monitoring commenced in January 2019 and shows that data collection had stopped in May 2021.

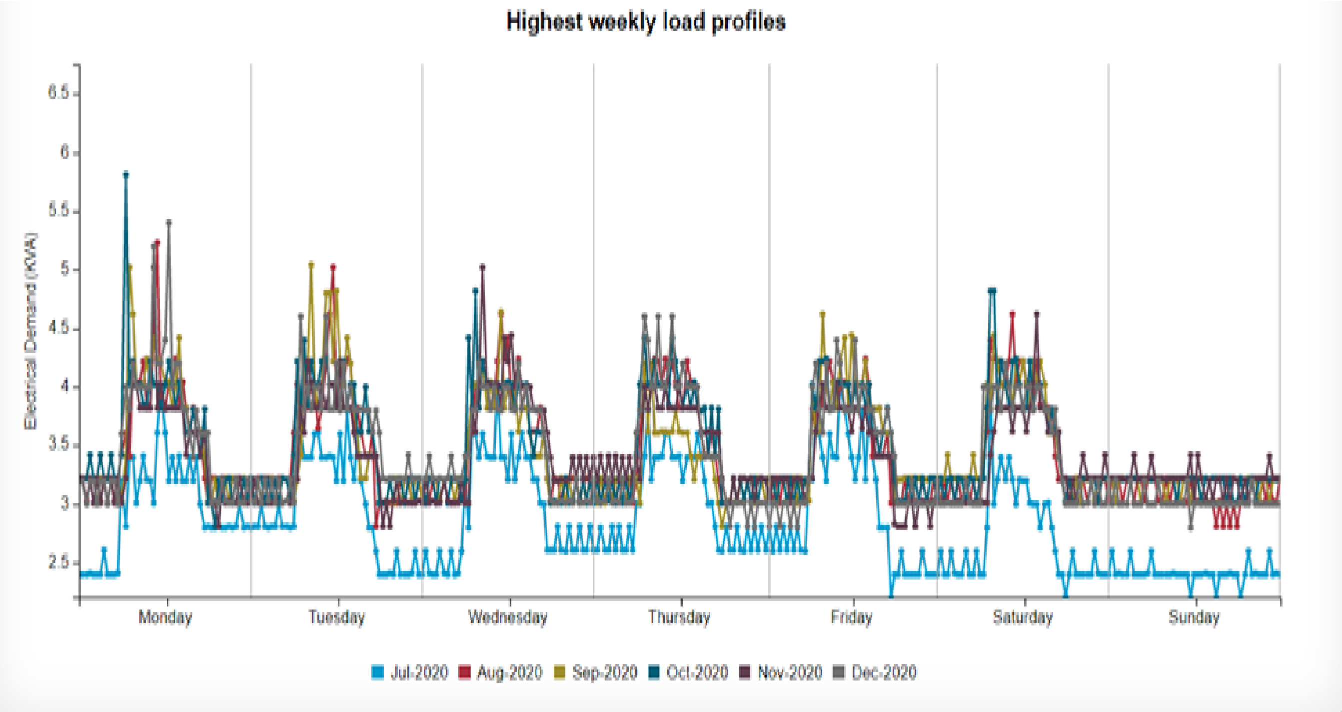


Figure 55: Highest recorded weekly energy load profile for Parade Chalets WWPS

The highest weekly electrical demand profile (kVA) for the months of July 2020, August 2020, September 2020, November 2020 and December 2020 are shown in Figure 55. The figure was obtained directly from SFD and shows that the electrical demand was the highest in those five weeks since the data monitoring commenced.

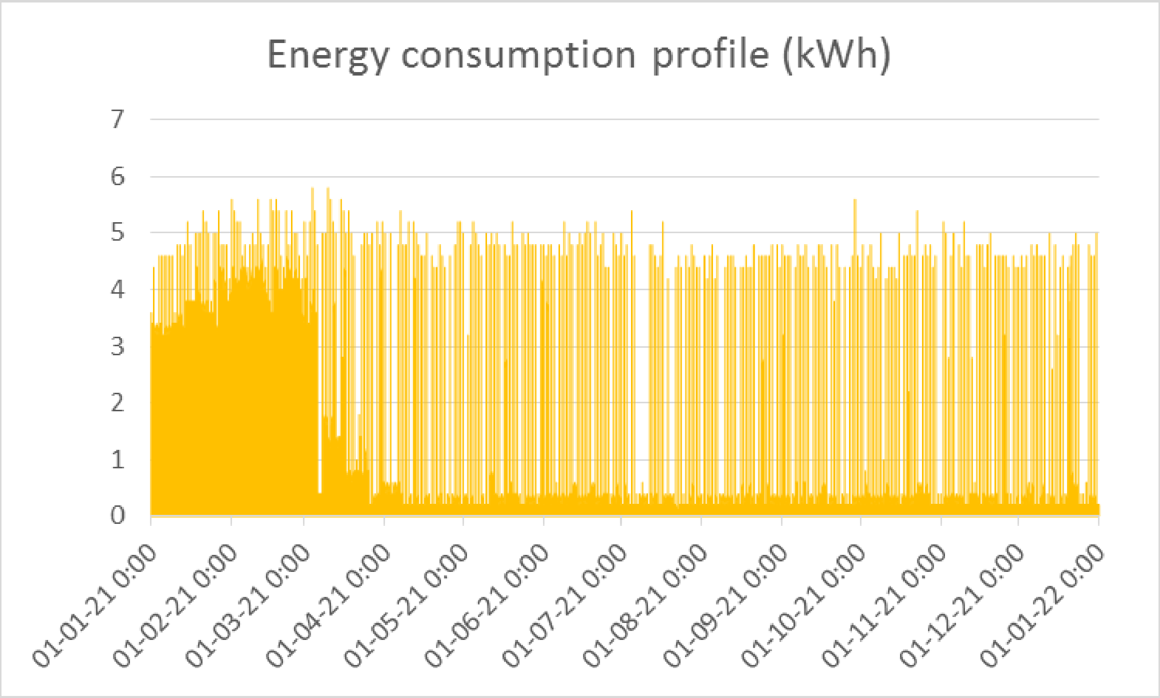
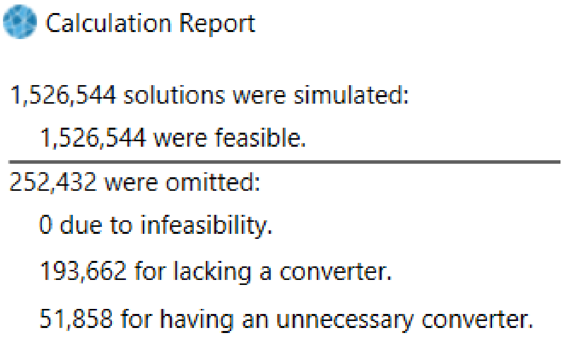


Figure 56: Energy consumption of Parade Chalets WWPS for year 2021 obtained from SFD (Excel)

From Figure 56 above, we observe that the energy consumption which throughout the year remains constant with consumption reading ranging between 0.2kWh to 5 kWh, with no distinct peaks. There is a fair amount of grouping occurring around January 2021 till March 2021. This grouping shows a minimum daily energy consumption 3 kWh, peaking to below 6 kWh. At around April 2021 the daily energy consumption tapers off to 0.2 kWh.

5.3.2 Results of HOMER simulation for Parade Chalets WWPS

Figure 57 below indicates that 1 526 544 solutions were simulated of which 252 432 were omitted, 193 662 omitted due to lacking a converter and 51 858 omitted for having a converter unnecessarily.



Calculation Report

1,526,544 solutions were simulated:

1,526,544 were feasible.

252,432 were omitted:

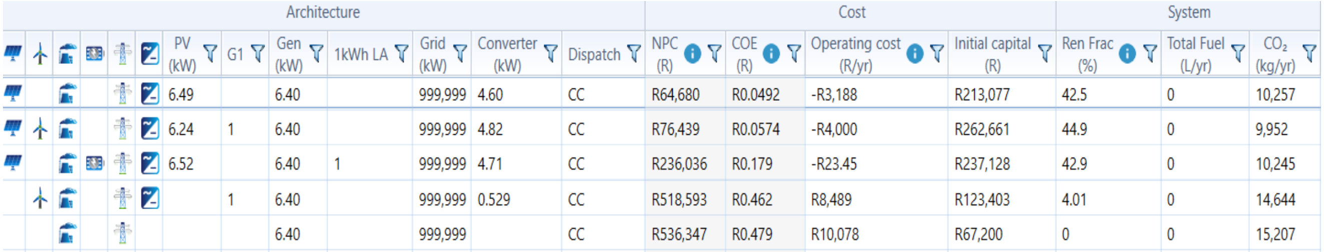
0 due to infeasibility.

193,662 for lacking a converter.

51,858 for having an unnecessary converter.

Figure 57: Simulated solutions for Parade Chalets WWPS

Figure 58 below indicates the top five optimization results for Parade Chalets WWPS. Of the top five, three results indicate the inclusion of SPV and two the inclusion of wind turbine where the COE ranges between R0.05 – R0.48 / kWh.



Architecture													Cost				System		
						PV (kW)	G1	Gen (kW)	1kWh LA	Grid (kW)	Converter (kW)	Dispatch	NPC (R)	COE (R)	Operating cost (R/yr)	Initial capital (R)	Ren Frac (%)	Total Fuel (L/yr)	CO₂ (kg/yr)
✓		✓		✓	✓	6.49		6.40		999,999	4.60	CC	R64,680	R0.0492	-R3,188	R213,077	42.5	0	10,257
✓	✓	✓		✓	✓	6.24	1	6.40		999,999	4.82	CC	R76,439	R0.0574	-R4,000	R262,661	44.9	0	9,952
✓		✓	✓	✓	✓	6.52		6.40	1	999,999	4.71	CC	R236,036	R0.179	-R23.45	R237,128	42.9	0	10,245
	✓	✓		✓	✓		1	6.40		999,999	0.529	CC	R518,593	R0.462	R8,489	R123,403	4.01	0	14,644
		✓		✓				6.40		999,999		CC	R536,347	R0.479	R10,078	R67,200	0	0	15,207

Figure 58: Optimization results for Parade Chalets WWPS

Figure 59 below indicates a proposal of adding 6.5 kW of PV and 6.4 kW of generator capacity. The operating cost, as defined by HOMER, is the annualized value of all costs and revenues. Therefore a reduced operating cost of -R3,188/ year would ultimately mean a saving, yielding an annualized saving of R63 343.00/ year. The RES investment has a payback of 17.8 years and an IRR of 9.11%.

Figure 59: Proposed RE system for Parade Chalets WWPS

Figure 60 below indicates the accumulative projected cash flow. However, the report indicates a simple payback of the proposed system at 17.8 years of the 20 year life span with carbon emissions decreasing to 10.257 tCO2e/year opposed to 15.207 tCO2e/year with grid energy. The proposed systems is a very small system (6.5 kW) if compared against. The proposed systems is a very small system (6.5 kW) if compared against

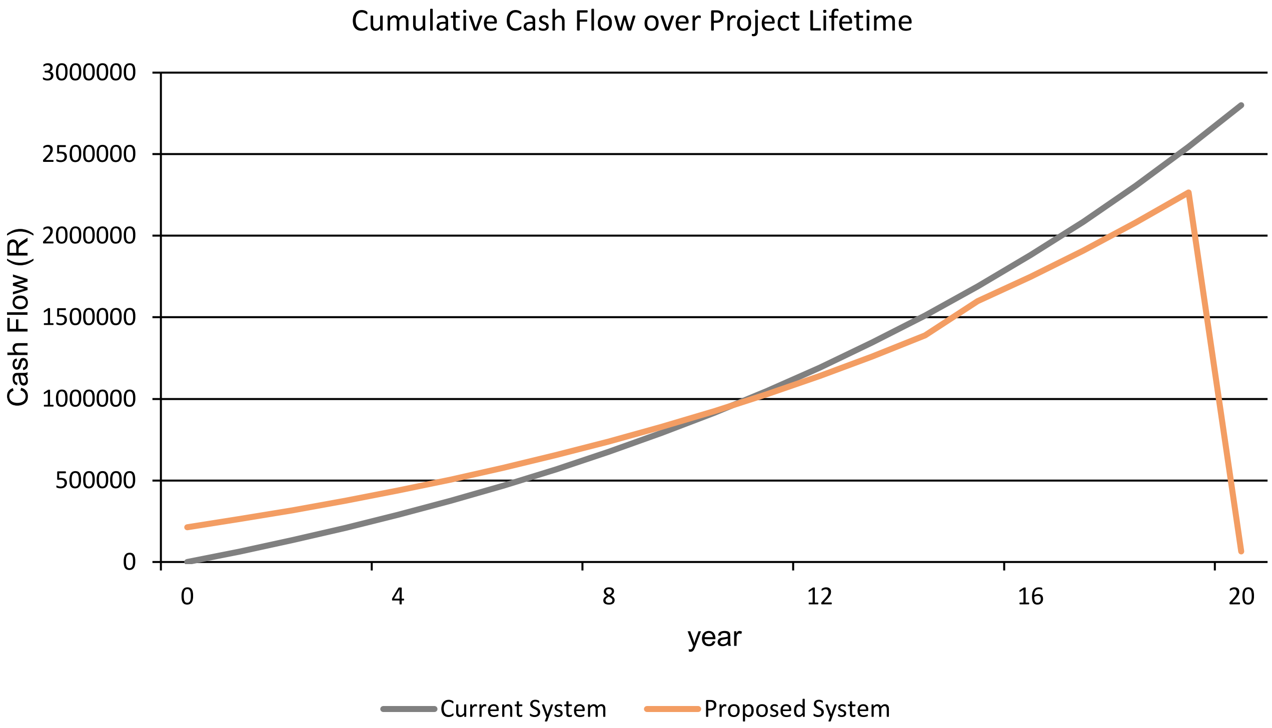


Figure 60: Feasibility summary of Parade Chalets WWPS

5.3.3 Discussion of Parade Chalets WWPS energy profile

Figure 54 indicated the monthly energy consumption profile for the years 2019, 2020 and 2021, which was directly obtained from the FSD. The figure shows that the energy consumption data monitoring had stopped in May 2021, however the data located under folder was up to June 2022. This could mean that these profiles were not automatically updated. From Figure 56 that at not stage was there a 0.0 kWh/ day indicating that this PS had functioned fully throughout the year.

5.3.4 Discussion of HOMER simulation Parade Chalets WWPS

Figure 60 indicates the feasibility of the proposed RES, however the results simulated that the simple buy-back would take around 17.8 years which differs from the graphs graphical display. This could be a fault in HOMER when generating the graph. The Initial proposed schematic design for Parade Chalets WWPS, as seen in Figure 42, did not result in the top five RES, as in the case of Royal Road WWPS, however, the HOMER simulations did revealed more feasible options. Figure 60 RES proposal was the result of the best-suited system with a COE at R0.05/ kWh. The forecasted COE for Parade Chalets WWPS was more in line with that found in SPV pumps for irrigation in the agricultural sector (Chandel, Nagaraju Naik and Chandel, 2015). This could be due to the fact that Parade Chalets has a very low energy consumption profile when compared to that of Wood Drive and Royal Road in Figures 45 and 49. Overall this RES is extremely cost effective and better suited for the environment where GHGs are concerned.

5.4 Results and discussion of HOMER simulation Hartleyvale WWPSs

5.4.1 Results of Hartleyvale WWPS energy profile

The results of the energy loading profile for Hartleyvale WWPS is indicated in Figures 61, 62 and 63 below. Figures 61 and 63 was obtained directly from SFD. The data of Hartleyvale WWPS year 2021 was fed in to Excel with Figure 63 as the result. This energy load profile was uploaded directly into HOMER for the modelling simulation of RESs.

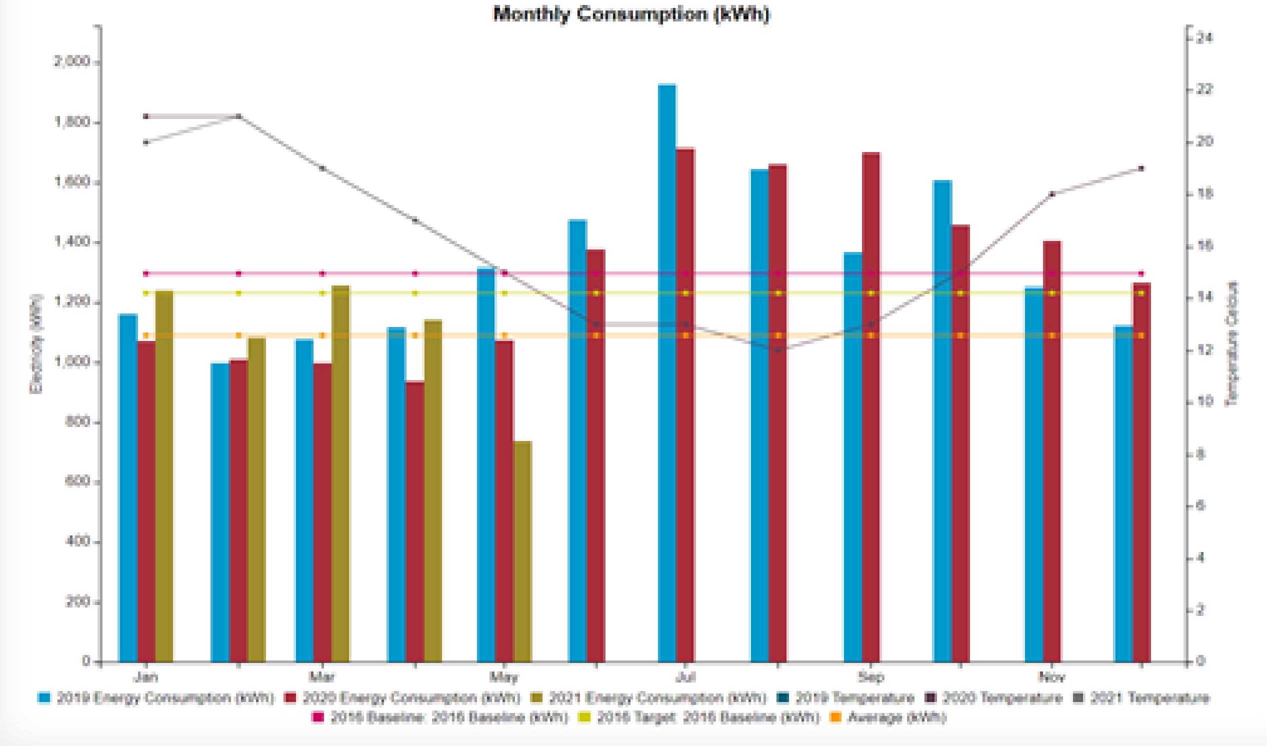


Figure 61: Average yearly energy consumption for Hartleyvale WWPS obtained from SFD

The monthly energy consumption profile for the years 2019, 2020 and 2021 are shown in Figure 61. The figure shows that the energy consumption data monitoring commenced in January 2019 for Hartleyvale WWPS. Figure 61 shows that data collection had stopped in May 2021.

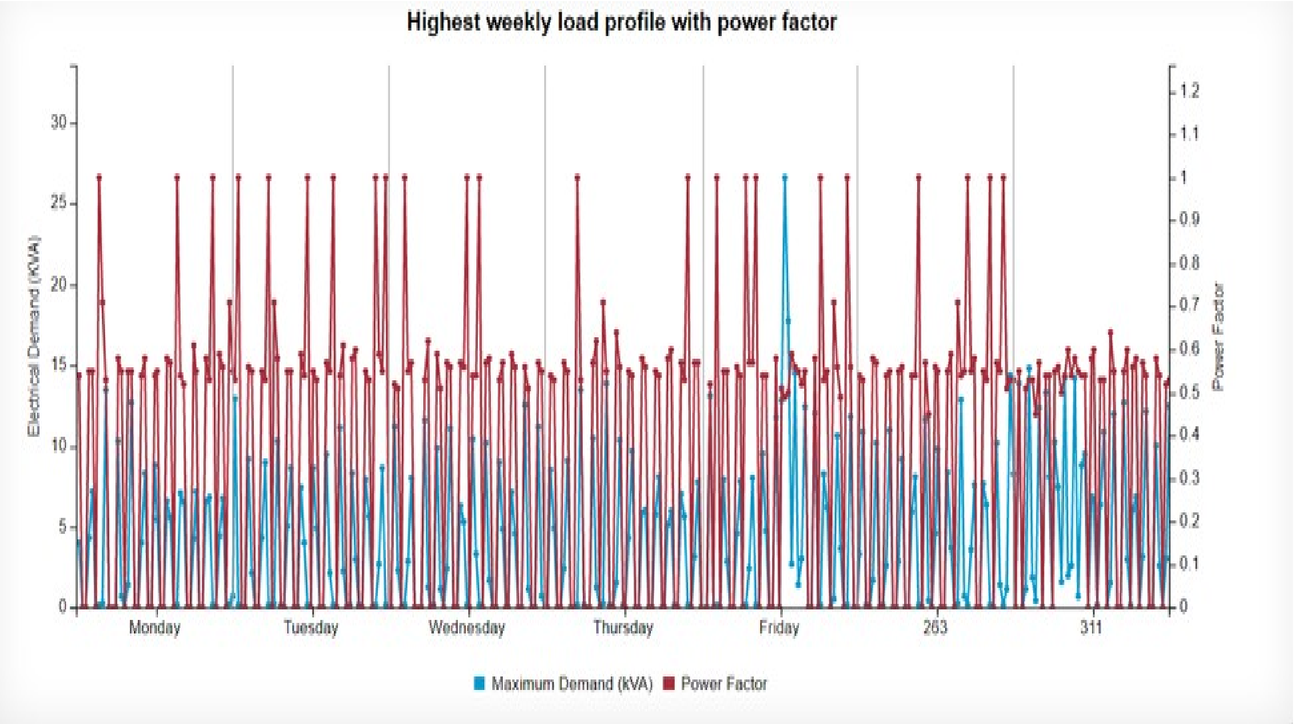


Figure 62: Highest recorded weekly electrical demand load profile for Hartleyvale WWPS obtained from SFD

Figure 62 was obtained directly from SFD and indicates the highest weekly electrical demand profile (kVA), however no weeks was shown. The figure and shows that the energy remained constant since the data monitoring commenced.

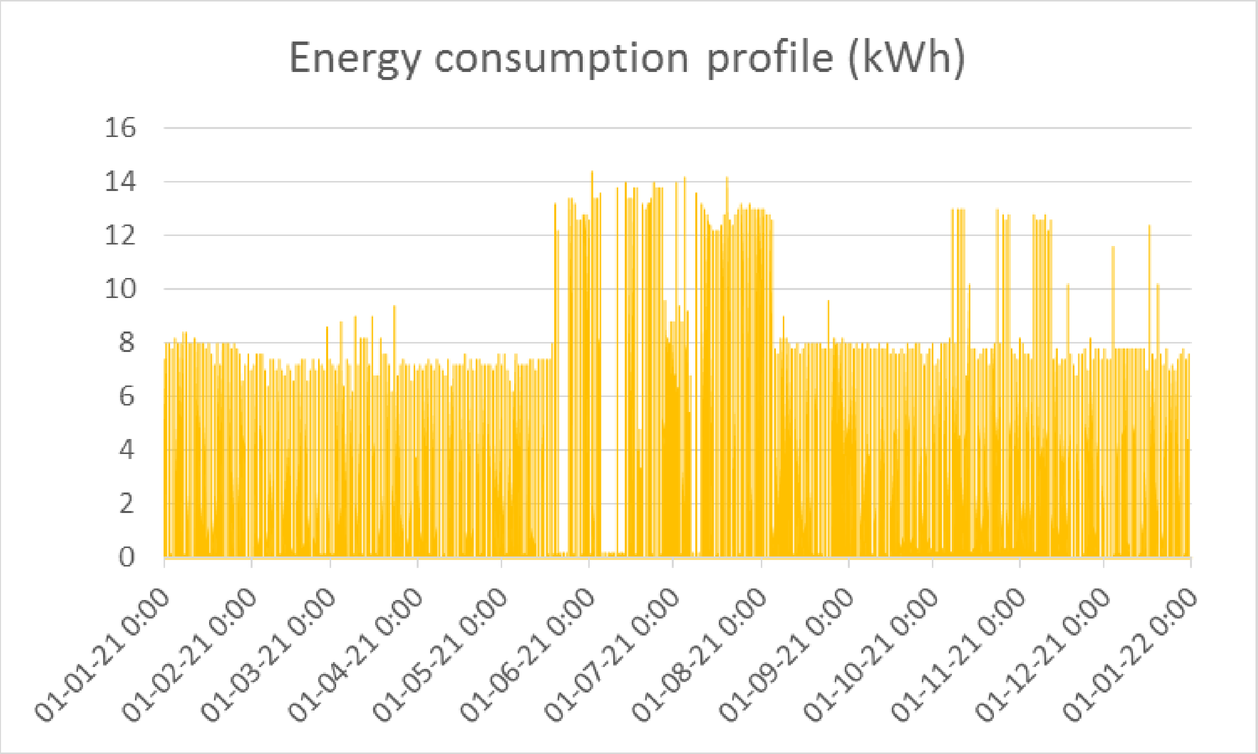
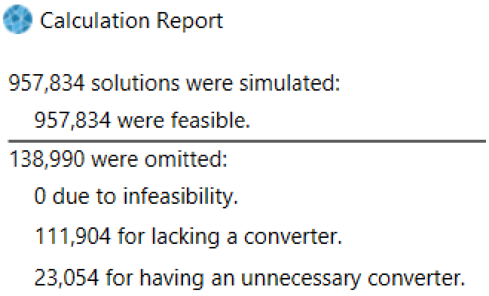


Figure 63: Energy consumption of Hartleyvale WWPS for year 2021 obtained from SFD (Excel)

From Figure 63 above, we observe that the energy consumption which throughout the year remains constant with consumption reading ranging between 0.1kWh to 7 kWh, with eight distinct grouping and peaks. There is a fair amount of grouping occurring around May 2021 till July 2021 and another three groupings in October and November 2021. The daily energy consumption remains constant between 0.1 kWh to 7 kWh, peaking to below 14 kWh for the two periods between May till July 2021 and October till November 2021.

5.4.2 Results of HOMER simulation for Hartleyvale WWPS

Figure 64 below indicates that 957 834 solutions were simulated of which 138 990 were omitted, 111 904 omitted due to lacking a converter and 23 054 omitted for having a converter unnecessarily.



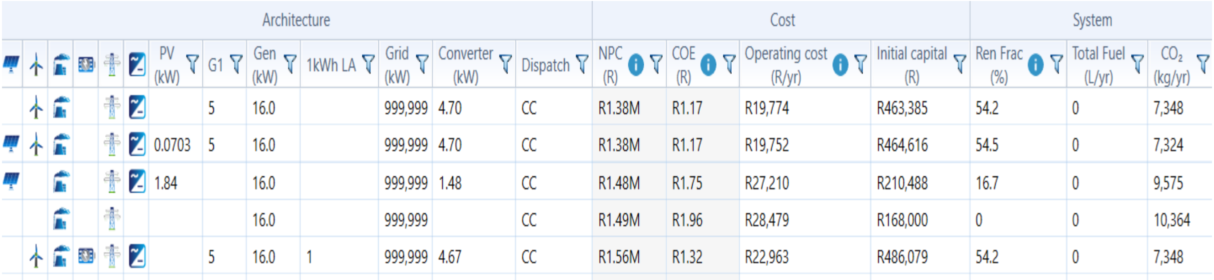
Calculation Report

957,834 solutions were simulated:
957,834 were feasible.

138,990 were omitted:
0 due to infeasibility.
111,904 for lacking a converter.
23,054 for having an unnecessary converter.

Figure 64: Simulated solutions for Hartleyvale WWPS

Figure 65 below indicates the top five optimization results for Hartleyvale WWPS. Of the top five, two results indicate the inclusion of SPV and three the inclusion of wind turbines. The COE ranges between R1.17 – R1.96 / kWh.



Architecture													Cost				System		
						PV (kW)	G1	Gen (kW)	1kWh LA	Grid (kW)	Converter (kW)	Dispatch	NPC (R)	COE (R)	Operating cost (R/yr)	Initial capital (R)	Ren Frac (%)	Total Fuel (L/yr)	CO_2 (kg/yr)
	●	●		●	●		5	16.0		999,999	4.70	CC	R1.38M	R1.17	R19,774	R463,385	54.2	0	7,348
●	●	●		●	●	0.0703	5	16.0		999,999	4.70	CC	R1.38M	R1.17	R19,752	R464,616	54.5	0	7,324
●		●		●	●	1.84		16.0		999,999	1.48	CC	R1.48M	R1.75	R27,210	R210,488	16.7	0	9,575
		●		●				16.0		999,999		CC	R1.49M	R1.96	R28,479	R168,000	0	0	10,364
	●	●	●	●	●		5	16.0	1	999,999	4.67	CC	R1.56M	R1.32	R22,963	R486,079	54.2	0	7,348

Figure 65: Optimization results for Hartleyvale WWPS

Figure 66 below indicates a proposal of adding 5.0 kW of wind generation and 16 kW of generator capacity in order to reduce operating costs toR19 774 / year and an annualized saving of R21 224.00/ year.

Figure 66: Proposed RE system for Hartleyvale WWPS

Figure 67 below indicates the accumulative projected cash flow. However, the report indicates a simple payback of the proposed system is not possible within the 20 year life span. However, the carbon emissions are decreased to 7.348 tCO2e/year in Figure 75 opposed to the 10.364 tCO2e/year simulated with grid energy.

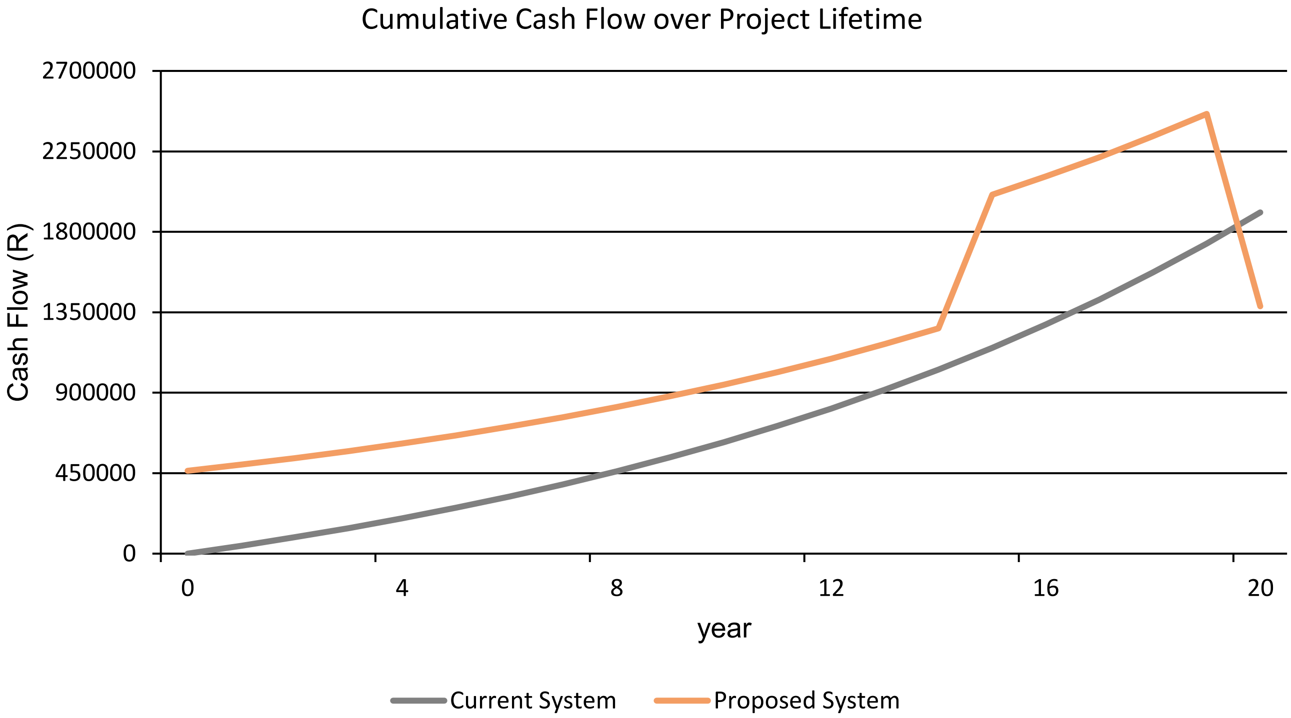
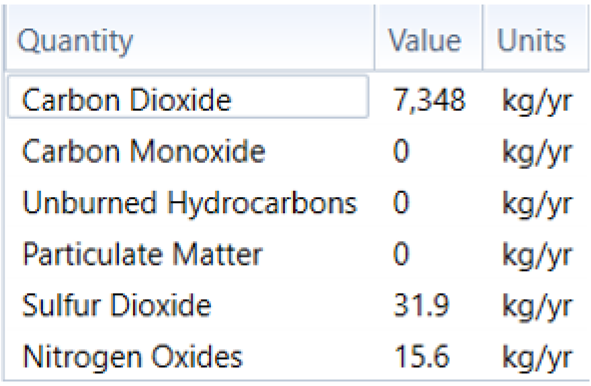


Figure 67: Feasibility summary of Hartleyvale WWPS



Quantity	Value	Units
Carbon Dioxide	7,348	kg/yr
Carbon Monoxide	0	kg/yr
Unburned Hydrocarbons	0	kg/yr
Particulate Matter	0	kg/yr
Sulfur Dioxide	31.9	kg/yr
Nitrogen Oxides	15.6	kg/yr

Figure 68: GHG emissions for proposed system

5.4.3 Discussion of Hartleyvale WWPS energy profile

Figure 61 indicated the monthly energy consumption profile for the years 2019, 2020 and 2021, which was directly obtained from the FSD. The figure shows that the energy consumption data monitoring had stopped in May 2021, however the data located under folder was up to June 2022. This could mean that these profiles were not automatically updated. From Figure 61 that at not stage was there a 0.0 kWh/ day indicating that this PS had functioned fully throughout the year.

5.4.4 Discussion of HOMER simulation Hartleyvale WWPS

The Initial proposed schematic design for Hartleyvale WWPS, as seen in Figure 43, did not result in the top five RES, as in the case of Royal Road WWPS, however, the HOMER simulations did revealed more feasible options. Figure 66 RES proposal was the result of the best suited system with a COE at R1.17/ kWh. Figure 67 indicates the feasibility of the proposed RES, however the results simulated that the simple buy-back would not be possible. However, HOMER does not allow the user to discard and not ‘salvage’ the proposed RES once the life span has been reached. Several researchers detailed the salvage of the RES to be at 75% of the original value as shown in Table 12. This would mean that over the 20 year lifespan there would be a slight return as the RES would end up costing less over the duration. Overall this RES is cost effective and better suited for the environment where GHGs are concerned.

5.5 Results and discussion of HOMER simulation loading spilt

Figure 69, 70 and 71 below indicates the energy-loading split for the proposed systems for Royal Road, Parade Chalets and Hartleyvale WWPSs respectively.

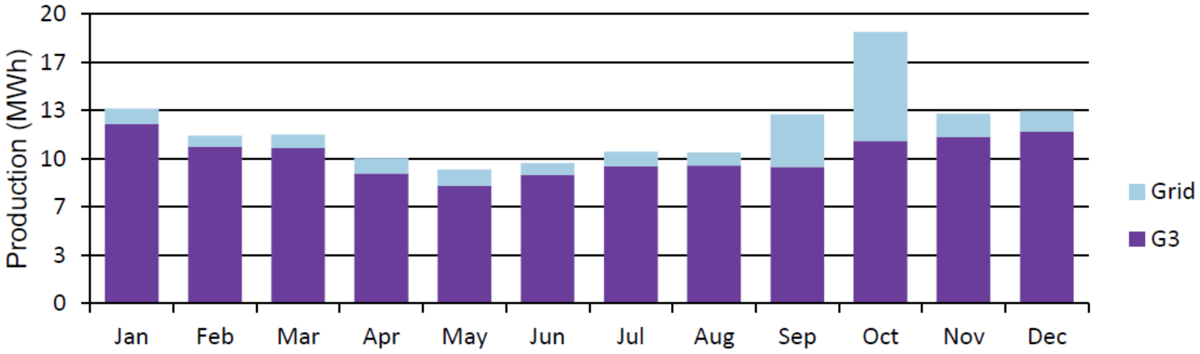


Figure 69 Royal Road WWPS proposed systems loading spilt

In Figure 69, we see that the use of grid energy is approximately less than 10% of the energy mix throughout the year, except for the month of October where this is estimated at around 40% of the month’s consumption. We also see that the proposed systems is able to supply 10 to just under 13MWh per year for the Royal Road WWPS scenario.

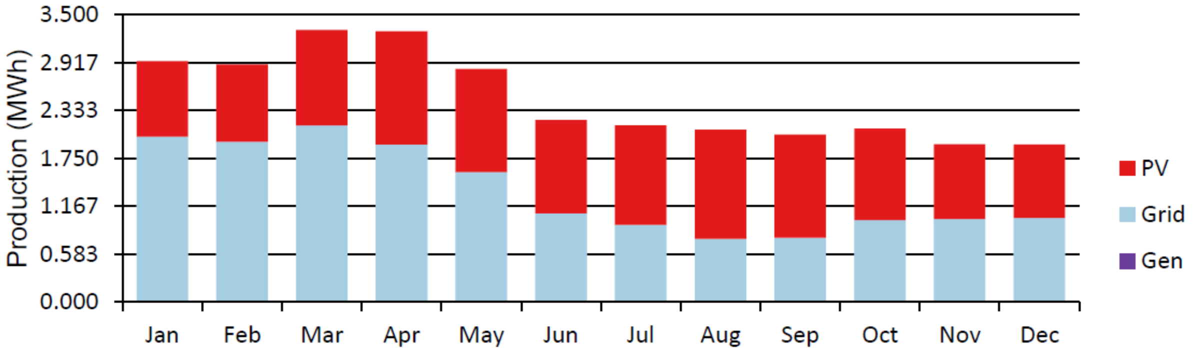


Figure 70 Parade Chalets WWPS proposed systems loading spilt

In Figure 70, we see that the use of grid energy is approximately less than 60% of the energy mix throughout the year. The months of January till May consuming the highest amounts of grid energy. It is important to note that Parade Chalets location is in central Cape Town within close proximity to Table Mountain, and for this reason could be adversely affecting the SPV. Notwithstanding that, the proposed solution in Figure 59 was found as the most feasible.

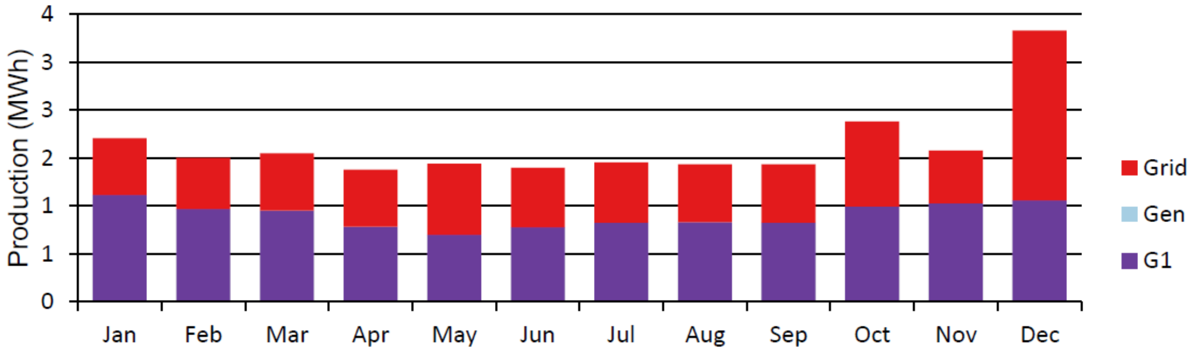


Figure 71 Hartleyvale WWPS proposed systems loading spilt

In Figure 71 above, we see that the grid energy consumption is approximately 55% of the energy mix throughout the year. The month of December is consuming the highest amounts of grid energy at 2361 kWh. We also see that the proposed systems is able to supply just under 9 MWh per year for the Hartleyvale WWPS scenario.

Is worth noting that a decrease in grid energy consumption was observed for all three case. These range from 60% dependency to as little as 10% dependency on grid energy to perform WWP.

5.6 Results and discussion of HOMER simulation SPV and wind resources

Figure 72 and 73 below represents the RE resources for wind and SPV for Cape Town respectively. The colour yellow with both the figures shows a strong potential and blue to black a weak potential ranging from a potential of 0 kW to 7 kW.

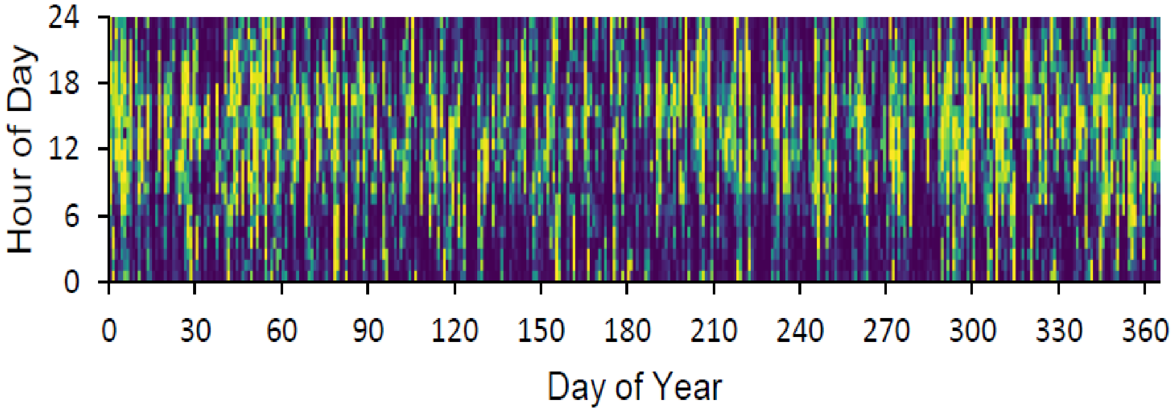


Figure 72 Renewable energy resources of wind in Cape Town

Figure 72 indicates that wind resources of Cape Town vary but is also present throughout the year. When analysing the graph from bottom 00:00am to 23:59pm we see that the wind is present throughout the hours of the day.

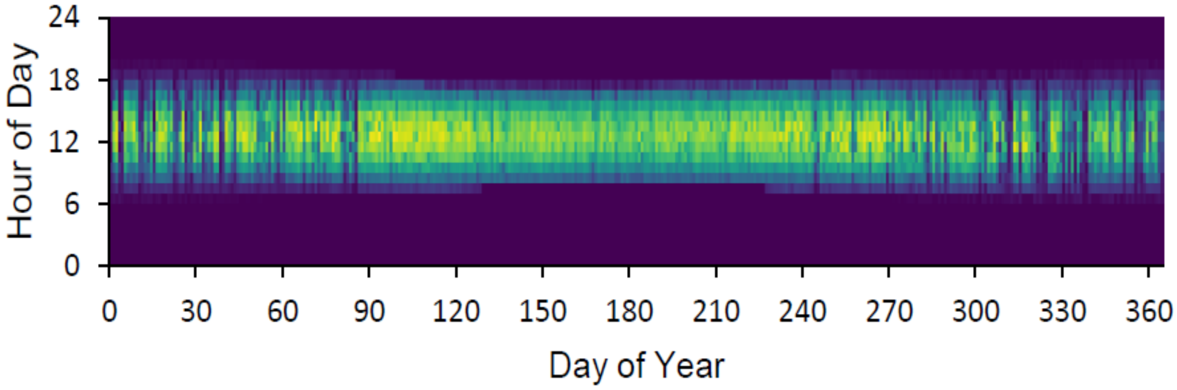


Figure 73 Renewable energy resources of SPV in Cape Town

Figure 73 above, indicates that solar resources of Cape Town present throughout the year between the hours of 07:00 am to 08:00 am till around about 18:00 pm to 19:00 pm day. We also note that the intensity tends to weaken around the 130 day to 220 day which is the winter season.

5.7 Results and discussion of designed generation mix with respect to the economic parameters

5.7.1 Royal Road WWPSs

When comparing the top five proposed system in Figure 51 against the design schematic of Figure 41 along with the sensitivity data in Tables 11 and 12, it was found that battery storage was not required in the of the proposals and wind turbines in only three. SPV as a stand-alone and/or in combination with wind made up four of the top five proposal. The initial capital costs ranged from R552 234 to R797 810, where the proposed system costed R722 714. The operating cost for the five proposals ranged between R74 608/ year to R83 693/ year.

5.7.2 Parade Chalets WWPSs

When comparing the top five proposed system in Figure 58 against the design schematic of Figure 42 along with the sensitivity data in Tables 11 and 12, it was found that battery storage was only required in one the of the proposals and wind turbines in two. SPV as a stand-alone and/or in combination with wind made up three of the top five proposal. The initial capital costs ranged from R67 200 to R262 661, where the proposed system costed R213 077. The operating cost for the five proposals ranged between –R3 188/ year to R10 078/ year.

5.7.3 Hartleyvale WWPSs

When comparing the top five proposed system in Figure 66 against the design schematic of Figure 43 along with the sensitivity data in Tables 11 and 12, it was found that battery storage was only required in one the of the proposals and wind turbines in three. SPV as a stand-alone and/or in combination with wind made up two of the top five proposal. The initial capital costs ranged from R168 000 to R486 079, where the proposed system costed R463 385. The operating cost for the five proposals ranged between R19 752/ year to R28 479/ year.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Wastewater pumping stations are an integral part of the wastewater treatment process. Approximately 20% of the world's energy consumption stems from the use of pumping systems. Increasing water scarcity has amplified the world's urban water cycles dependency on energy for water delivery and treatment. Furthermore, energy access can be an obstacle to urban cities resulting in both energy and water shortages as well as increased levels of water pollution. This research aims to answer the question: *"What sort of RESs would be able to meet the energy requirements of WWPSs in Cape Town and would it be feasible to invest in such infrastructure as opposed to the dependency of conventional grid power and back-up diesel generators?"* From this research we see that SPV and wind has a strong potential to provide RE for the function of wastewater pumping, however all the systems had the back of diesel generators and grid energy simulated as the preferred option. The results of all of three case studies indicated that RE could supply energy for WWP, where these figures were at 90%, 45% and 40% respectively. The price of energy across all three cases were reduced drastically with a COE ranging between R0.05 till R1.51/kWh. This dissertation successfully answered the research question with regards to the ability of RES being able to meet the energy demands of WWPS in opposition to fossil fuel energy dependence. The results display the feasibility of investing in RE technology for Cape Town's WWPSs and is demonstrated with all three cases concerning the savings and around GHG emissions. The significance of this research means that it is possible to mitigate against 8% electricity consumption and 10% GHG emissions stemming from the CCT LMG by implementing substitute RESs within the WWPSs in Cape Town. RESs within WWPSs is completely feasible when comparing all three case study results of CCTs PSs. Furthermore, this study showed that CCTs WWP specific energy intensity is in line with global trends for countries and urban cities in India and New Zealand as indicated in Tables 4 and 5 and this figure could be used when planning wastewater infrastructure in Cape Town.

Findings and recommendations

The global scenario concerning energy studies in WWT, as a whole, is piecemeal and disjointed. There remains no consensus in a single approach standardized energy studies for WWT facilities. The differences in approach differ vastly from KPI's and methodologies. The most suitable KPI for energy intensity for WWP was found to be kWh/m³ and not kWh/ kg COD, as no water is treated within a WWPS, but transport or pumped. WWT accounts for 0.5% of the carbon emissions within Cape Town. Energy consumption for WWT for countries around the globe can range between 0.5% till 4%, however there is no such estimate for South Africa. South Africa is regarded as having RE resources that are viable for exploitation. Cape Towns wind and solar RE resources are more viable than in other parts of the South Africa. The CCT LMG has several promising RE projects that are currently underway with regards to net-zero carbon within the WWT for the city, however from a WWP perspective, this is yet to be undertaken.

Areas for further research

The data obtained in this dissertation is comprehensive, relevant and recent enough for employment in further technological development within Cape Town's WWT energy landscape, as several similar projects has been launched. The methodology employed on this study, could be replicated and applied to water pump station facilities. Finally, recent developments with regards to the energy landscape, Cape Town has made it possible for energy generators to sell energy into the grid for payment (Luckhoff, 2022), making RESs in WWP even more feasible. This recently adopted policy is a monumental shift in the energy landscape and would present an opportunity to research and evaluate costing models, taking into account the impact of emission costs, as opposed to simple payback models.

7. References

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8. Annexures (See attached)

Annexures (See attached)

Appendix A. Wood Drive WWPS Site Photographs

/../Save measured values
Save as : protected format
Preset time range : 1 day
From : 29.07.2019 00:00:00
To : 22.08.2019 08:46:03
Start copying process
X Back
Help = Keep the jog/shuttle dial pressed


PRESSURE
27.42
kPa
FLOW METER
0.0
l/s
TOTALIZED FLOW (m³)
DATA LOGGER
51,4
52,3
51,7
-0,0
27,0
20,4


Schneider Electric
Magelis
GENERATOR AVAILABLE
GENERATOR TRANSFER ON
GENERATOR COMMON ALARM
GENERATOR E/STOP ACTIVATED
GENERATOR E/STOP


DEEP SEA ELECTRONICS