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ELECTRICAL ENGINEERING

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POWER GENERATION USING MODULAR WASTE INCINERATION POWER PLANT IN DEVELOPING COUNTRIES

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FOREWORD

The topic of this Master thesis was received from Woima Finland Oy. I would like to thank Woima Finland Oy for giving the opportunity to write this thesis on such an interesting subject. I would like to thank my instructor Tapani Korhonen for support and guidance during the thesis.

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My warmest thanks are to my family for great support and encouragement during the thesis. Thanks also to my friends for their valuable encouragement during studies.

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SYMBOLS, ABBREVIATIONS AND TERMS

Greek symbols

α, β	Combustion parameters
ΔT	Temperature change
ε	Permittivity of the material
η	Efficiency
ρ	Density of the material
ω	Rotational velocity

Other symbols

A	Area of the capacitor plates
c_p	Specific heat of storage material
C	Capacitance
C_tot	Total capacitance
d	distance between capacitor plates
$\mathrm{d}V$	Total voltage change
E	Stored energy
F	Combustion air flow
F_2	Leak air flow
g	Gravitational constant
h	Height
I	Current
J	Moment of inertia
L	Inductance

m	Mass
NO_x	Nitrogen oxides
O_2	Oxygen
P_N	Rated power
q	Stored charge
Q_b	Target steam flow
Q_t	Amount of heat
Q_w	Water flow rate
r	Radius
R_{tot}	Total resistance
S	Burning grate speed
U_C	Voltage between capacitor plates
U_L	Voltage across the coil
V	Volume of water

Abbreviations

AC	Air conditioning
APC	Air pollution control
BESS	Battery energy storage system
BFB	Bubbling fluidized bed
BGS	British Geological Survey
CAES	Compressed air energy storage
C&I	Capital and investment
CFB	Circulating fluidized bed

CG	Centralized generation
CHP	Combined heat and power
COE	Cost of electricity
CPP	Critical peak pricing
DC	Direct current
DG	Distributed generation
DLC	Direct load control
DR	Demand response
DSM	Demand side management
EIA	Energy Information Administration
EE	Energy efficiency
EES	Electrical energy storage
ERC	Energy Regulatory Commission
FBC	Fluidized bed combustion
FES	Flywheel energy storage
GC	Grate combustion
HFO	Heavy fuel oil
HOMER	Hybrid optimization of multiple electric renewables, a simulation software
IPP	Independent power producer
KNBS	Kenya National Bureau of Statistics
KPLC	Kenya Power and Lightning Company
Li-ion	Lithium-ion
LNG	Liquefied natural gas
MSW	Municipal solid waste

NaS	Sodium-sulphur
Ni-MH	Nickel-metal hydride
NPC	Net present cost
NREL	National Renewable Energy Laboratory
O&M	Operating and maintenance
PHS	Pumped hydroelectric storage
RES	Renewable energy source
RTP	Real time pricing
SCES	Super capacitors energy storage
SMES	Superconducting magnetic energy storage
TES	Thermal energy storage
TESS	Thermal energy storage system
TOU	Time of use
UPS	Uninterruptible power supply

Terms

Annual generation capacity	Maximum output of a power plant during a year.
Annual production	Actual production of a power plant during a year.

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ABSTRACT

Standard of living rises and amount of waste generated increases in developing countries. Population and need for energy also grows, creating opportunities for exploit modular waste incineration power plants which are small incinerators and can be located near populated areas. The modular incineration power plant enables an appropriately sized incineration plant by combining incinerator units. Waste incinerated can regionally be collected and generated energy can be recycled back to same region.

The object of the thesis is to study balancing of power generation of waste incineration plant and to find out the capital costs and operating and maintenance (O&M) costs of the plant. The aim is also to determine factors affecting balance between electricity generation and consumption in general. Pilot city of the project is Nairobi, the capital of Kenya, and the purpose is to create a model that can also be applied to other developing countries. The study is carried out based on the information from the pilot city and other related material. The literature review at the beginning of this thesis examines common incineration power plant techniques and more specifically the grate incineration technique and project implementation used in the project. The empirical study analyses factors affecting balance between electricity generation and consumption in Nairobi. Cost modelling is based on the Homer optimization program, which uses generation capacity of waste incineration power plants and adapts consumption to generation.

As the results of the thesis were obtained methods used to control the production of the waste incineration power plant and a cost model for the capital costs of the study as well as operating and maintenance costs. The cost model is created based on other similar projects and is indicative and changes according to the project implementation. In addition, the result was a study factors contributing to the balance between electricity generation and consumption in Nairobi. The review covered existing energy generation in Kenya, demand side management methods and energy storage technologies.

KEYWORDS: Modular waste incineration power plant, distributed power generation, balancing power generation and consumption, energy storage systems, Homer

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TIIVISTELMÄ

Kehitysmaiden elintaso nousee ja niin myös samalla syntyvän jätteen määräkin kasvaa. Väestö ja energian tarve kasvavat myös, mikä luo mahdollisuuksia hyödyntää modulaarisia jätteenpolttolaitoksia, jotka ovat pieniä polttolaitoksia ja voidaan sijoittaa lähelle asutusta. Modulaarinen polttolaitos mahdollistaa sopivan kokoisen polttolaitoksen yhdistämällä polttolaitosyksiköt. Poltettava jäte voidaan kerätä lähiympäristöstä ja tuotettu energia voidaan kierrättää takaisin samalle alueelle.

Diplomityön tavoitteena on tutkia jätteenpolttolaitoksen sähköntuotannon tasapainottamista ja selvittää laitoksen pääomakustannukset sekä käyttö- ja ylläpitokustannukset. Tavoitteena on myös määrittää yleisesti sähkön tuotannon ja kulutuksen väliseen tasapainoon vaikuttavat tekijät. Projektin pilottikaupunki on Kenian pääkaupunki Nairobi, ja tarkoituksena on luoda malli, jota voidaan soveltaa myös muihin kehitysmaihin. Tutkimus toteutetaan pilottikaupungista saatujen tietojen ja muun siihen liittyvän aineiston perusteella. Työn alun kirjallisuuskatsauksessa tarkastellaan yleisiä polttolaitostekniikoita sekä tarkemmin projektissa käytettyä arinapolttotekniikkaa ja projektin toteutusta. Empiirisessä tutkimuksessa analysoidaan tekijöitä, jotka vaikuttavat sähköntuotannon ja kulutuksen väliseen tasapainoon Nairobissa. Kustannusten mallintaminen perustuu Homer optimointiohjelmaan, jossa energian tuotantokapasiteettina käytetään jätteenpolttolaitosten tuotantokapasiteettia ja kulutus sovitetaan tuotantoon.

Työn tuloksina saatiin selvitys jätteenpolttolaitoksen tuotannon ohjauksessa käytettävistä menetelmistä sekä kustannusmalli tutkimusprojektin pääomakustannuksista sekä käyttö- ja ylläpitokustannuksista. Kustannusmalli on luotu muiden vastaavien projektien pohjalta ja se on suuntaa antava sekä muuttuu projektin toteutuksen mukaan. Lisäksi tuloksena saatiin selvitys Nairobin sähköntuotannon ja kulutuksen välistä tasapainoa edesauttavista tekijöistä. Tarkasteluun otettiin Kenian olemassa oleva energian tuotanto, kysynnän hallintamenetelmät sekä energian varastoiminen eri tekniikoin.

AVAINSANAT: Modulaarinen jätteenpolttolaitos, hajautettu sähkön tuotanto, sähkön tuotannon ja kulutuksen välinen tasapaino, energian varastointijärjestelmät, Homer

1 INTRODUCTION

1.1 Background of the thesis

Energy demand is increasing also in developing countries while amount of population grow. New sources of energy are also needed to replace fossil fuels. Preferably, existing local resources can be utilized. Population growth increase also amount of waste generated. These issues can be solved with waste incineration power plant. Waste can be incinerated at the incineration power plant and the plant generates energy accordingly.

Topic of this thesis has been obtained from Woima Finland oy. It is small consulting company that includes waste incineration power plants as one sector. This thesis is part of a project in Nairobi, the capital of Kenya. This project is intended to be a pilot project to carry out similar projects in other cities in developing countries. The project creates an operating model that can be utilized with small changes to other cities.

Waste incineration power plant provides opportunity to create a new energy generation model in which generated waste can be converted into energy. The model becomes decentralized when waste incinerators are smaller and more densely located. In the decentralized model, waste and energy transfer distances are shorter when incinerated waste can be collected near the incinerator and generated energy can be returned back to this region. This energy generation model solves both energy generation and waste management in that area.

1.2 Objectives of the thesis

An objective of this thesis is to examine control of waste incineration power plant when producing energy in different forms. The purpose is also to clarify capital as well as operating and maintenance (O&M) costs of incineration power plant and to build a simplified cost model using Homer optimization program. Homer is the software designed to be used for micropower optimization and it contains three usage features: simulation, optimization and sensitivity analysis. The cost model created for simulation and optimization provides guidelines for costs and can be used in other waste incineration power plant projects. (Homer Energy 2018b.)

This study surveys also factors affecting balance between power generation and consumption. This is being explored by mapping current forms of energy generation in Kenya and factors influencing energy demand. Different forms of energy storage for electrical and thermal energy are also explored.

The objectives of the thesis can be presented in the following way:

1. Investigate power generation control of waste incineration power plant.
2. Solve capital and O&M costs of waste incineration power plant.
3. Build a simplified cost model using Homer optimization program.
4. Examine factors affecting balance between power generation and consumption.

1.3 Scope and structure of the thesis

The thesis is part of a larger project on decentralized waste management and power generation optimization. This thesis focuses on power generation and optimization. Due to this waste management and logistics are neglected in this work.

The structure of the thesis is divided into a literature review and an empirical study. In addition to these sections, there is an introduction as well as conclusions and a summary. This structure is illustrated in Figure 1.

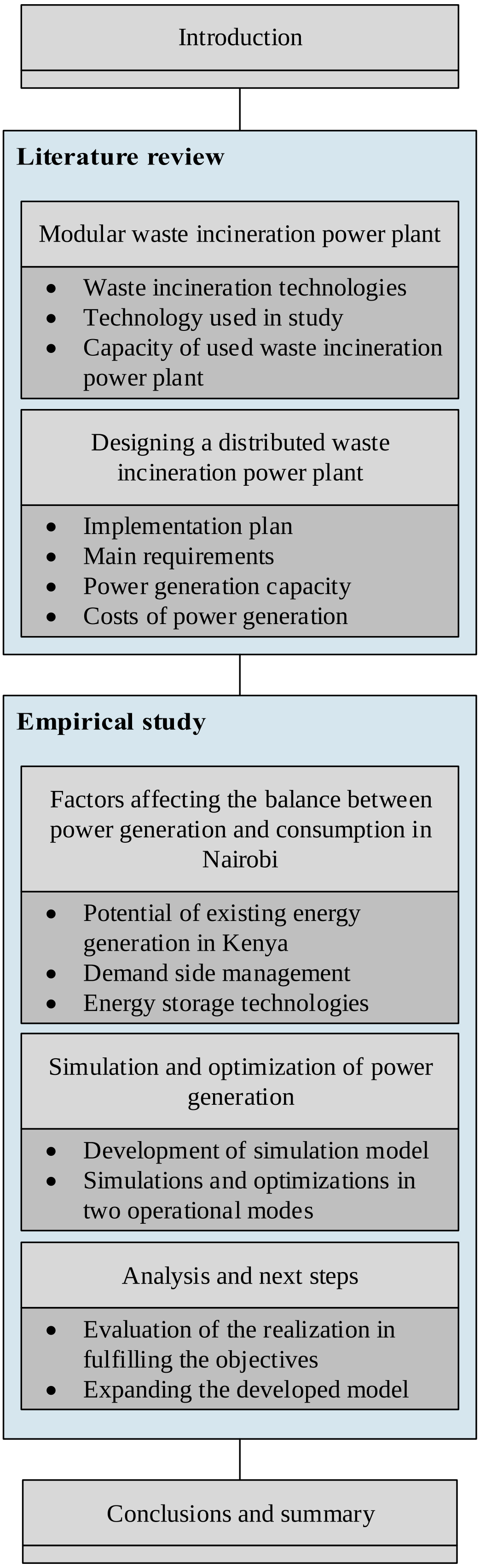


Figure 1. Structure of this thesis.

The literature review follows the introduction and introduces waste incineration power plant technology used in the study. The conditions of technical operation of the incineration plant are also surveyed. Chapter 2 also provides general overviews of incineration technologies and a modular waste incineration power plant used in study. Chapter 3 explores implementation of distributed power generation using waste incineration power plants, from implementation plan to control of generation in waste incineration power plants, namely a case study for capital Nairobi in Kenya.

The empirical study begins in Chapter 4, which inspects options for balancing power generation and consumption in Nairobi and Chapter 5 examines utilization of the Homer micropower optimization model in simulations of cost model. Chapter 6 analyses solutions found in the study to control of power generation of waste incineration power plant and considers development steps, such as applying a waste incineration solution to other similar cities in developing countries. Finally, conclusions and summary illustrate the main research findings.

The following are assumptions and restrictions done in this thesis:

- Examination of power generation and consumption is limited to generation capacity of waste incineration power plants, except for Chapter 4.
- Waste incinerators supply energy only to the Nairobi area.
- Simulation model has to be adapted to the program and then other energy generation is excluded in simulations of Chapter 5 and used loads are adapted to generation.
- Steam generation is left out in simulations of Chapter 5.
- Waste management and logistics are left out.

2 MODULAR WASTE INCINERATION POWER PLANT

This chapter introduces features of a distributed power system and techniques which are used incineration power plants. In addition, the incineration power plant used in the study and its capacity are examined in more detail. Distributed power system means a generation structure where distributed generation (DG) sources can supply power directly to distribution network and to customers (Farret & Simões 2006: 10). Typically, DG uses several small generators instead of a few large generators. In addition, DG is usually associated with microgrids and smart grids, and these are an integral part of a distributed power generation system. Renewable energy and energy storage technologies are also commonly used in distributed power generation systems.

Distributed waste incineration power plant is a modular incineration power plant, which consists of modules. This allows its size to be selected according to customer needs and placed in a relatively small area. Alternative to distributed waste incineration power plant system is centralized generation (CG), where power generation is concentrated in large power plants. This leads to a weakness in the CG model, as the CG model requires investments in distribution and transmission networks. Electricity must also be distributed from electricity producing plants to final consumers, which increases power losses in electricity distribution network. For these reasons, DG is a better option to implement waste incineration power plants. (Mojumdar, Himel & Kayes 2015: 2; Gharehpetian & Agah 2017: 370.)

Technologies used in DG can be divided into three groups: fuel-based technologies, technologies based on renewable energy and energy storage-based technologies. The fuel-based technologies are relatively new types of distributed generation technologies, including the distributed waste incineration power plant used in the study. Figure 2 shows a typical distributed power generation system including typical features of DG. (Gharehpetian & Agah 2017: 6–9.)

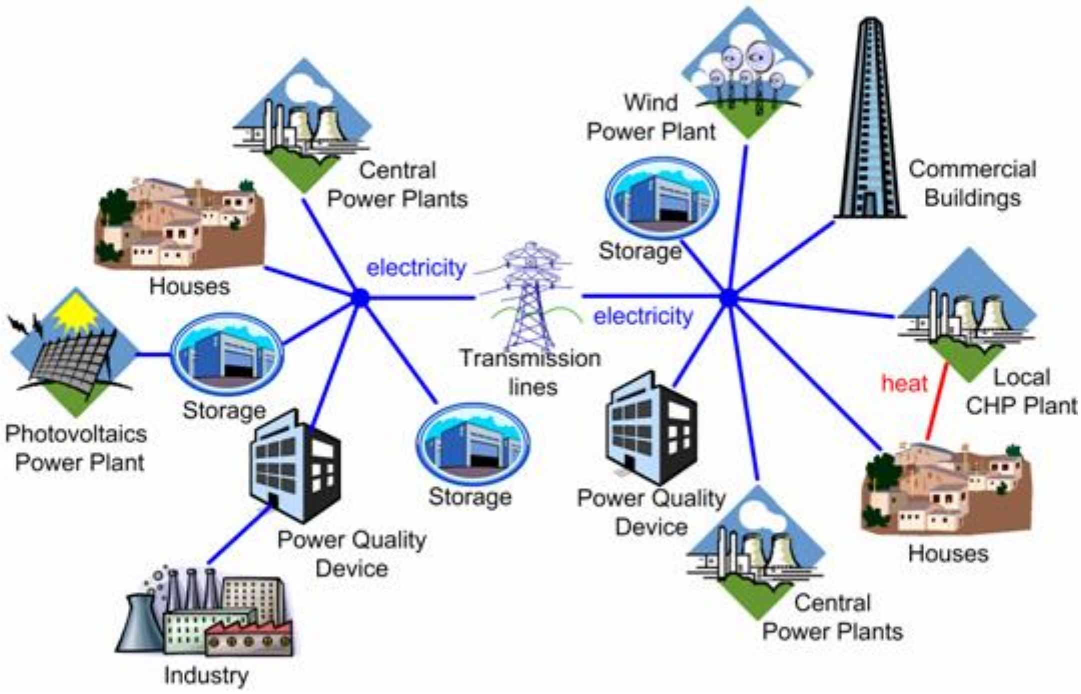


Figure 2. Distributed power system model having two microgrids (Liserre 2008: 15).

Figure 2 illustrates typical features of the distributed power system:

- Power generating units are relatively small and power system utilizes energy storage technologies.
- Energy sources are near consumers to reduce transmission and distribution losses and to meet customer needs.
- System utilizes renewable as well as combined heat and power energy sources.

2.1 Waste incineration technologies

Generating energy by waste incinerator is based on energy from waste when it is incinerated at a waste incineration power plant. Municipal solid waste (MSW) is usually used as a fuel for waste incineration but there are several types of waste incineration technologies. The two most commonly used waste incineration technologies are grate combustion (GC) and fluidized bed combustion (FBC). Of these, grate combustion is more commonly used technology and is used in small and medium size incineration plants. Fluidized bed combustion is a newer technology and is well suited for more environmentally combustion. (Poltto ja palaminen 2002: 466, 490.)

2.1.1 Grate technology

Waste incineration using grate technology follows similar steps as combustion by other combustion methods. In grate combustion technology we can separate three to four main stages:

- removal of moisture
- pyrolysis and volatile combustion
- residual char combustion.

Depending on viewpoints, the fourth stage of combustion can still be combustion of gases. Moisture is removed because of heat radiation in a furnace. When moisture has left waste, it follows pyrolysis, where most of burning occurs. During the pyrolysis phase are generated gases and tares that burn very well in flames if there is enough oxygen. After the pyrolysis phase, combustible fuel remains carbon which burns from surface at proper temperature without flame if there is enough oxygen. Typically, this combustion phase is slow and requires relatively more grate surface than pyrolysis. Burn releases gases that burn in the fourth stage at the top in the furnace. Basic structure of a furnace made with grate technology is shown in Figure 3. (Poltto ja palaminen 2002: 466–468; Vesanto 2006: 30–31.)

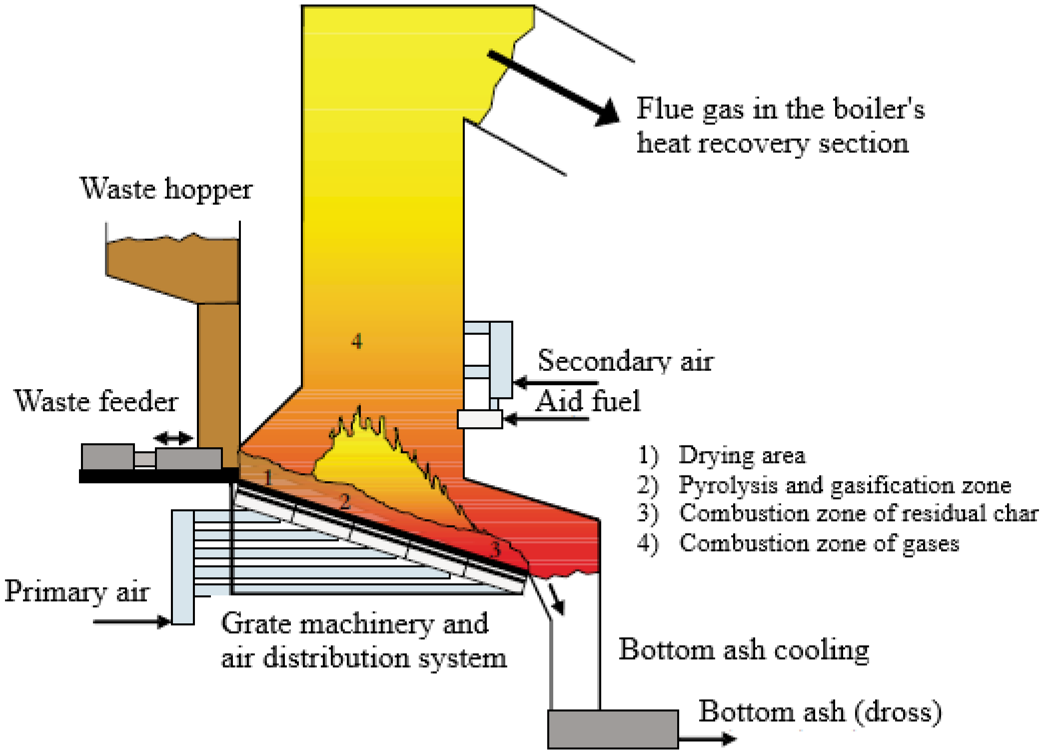


Figure 3. Basic structure of a grate furnace designed for waste incineration (Modified from: Vesanto 2006: 31).

Figure 3 demonstrates principle of the grate furnace. Figure shows waste feed system through which waste is transferred to the furnace. In the furnace are different combustion zones where waste is burned at different stages. Figure also shows air inlets and air distribution system needed for combustion, flue gas flow as well as separation of bottom ash from waste.

2.1.2 Fluidized bed technology

In FBC, waste is incinerated in a fluidized bed of glowing sand and ash. Fuel moves and mixes continuously on a floor and gas and heat transfer is very efficient. Burning involves the same steps as the grate technology, in other words the removal of moisture, pyrolysis and residual char combustion. The FBC technology is considerably newer compared to grate technology but has now been in industrial use for more than 30 years. Advantage of FBC is that the technology is particularly suitable for low-grade fuels. In addition, FBC allows use of cheap desulphurization and technology does not require much pre-treatment of fuel.

The FBC can be divided into two different main applications: bubbling fluidized bed (BFB) and circulating fluidized bed (CFB). The BFB technology is the first version of these and it is specially designed for combusting inferior quality fuels such as waste and sludge. The BFB technology is also well suited for small industrial applications. Later developed CFB technology is derived from the BFB technology but is more advanced in sulphur removal, efficiency and scale compared to BFB technology. (Koornneef, Junginger & Faaij 2006: 20–21.)

In the BFB technology, sand or mineral crushes are used as base material of a bed, and remainder of a material is fuel ash. In waste incineration, proportion of ashes may be quite high. Incinerated waste is fed into a furnace by means of a feed system, preventing mixing of gas streams. Most of combustion air is fed to the bed through bottom of the furnace as a primary air. Rest of required air is fed over the bed as a secondary air. Coarse ash and non-combustible material involved in waste are removed from bottom of furnace, but fine ash and powered bed material pass through flue gas out of furnace and separate from flue gas in the boiler and flue gas cleaning.

In the BFB technology, flue gases are derived from furnace into a pre-cooling chamber where flue gases are cooled and separated from vaporized metals and inorganic materials. Shape and size of furnace is selected so that flue gas flow leaving the furnace is low and the bed material particles do not originate according to exhaust gas flow. Basic structure of the furnace with BFB technology is shown in Figure 4. (Vesanto 2006: 31–33.)

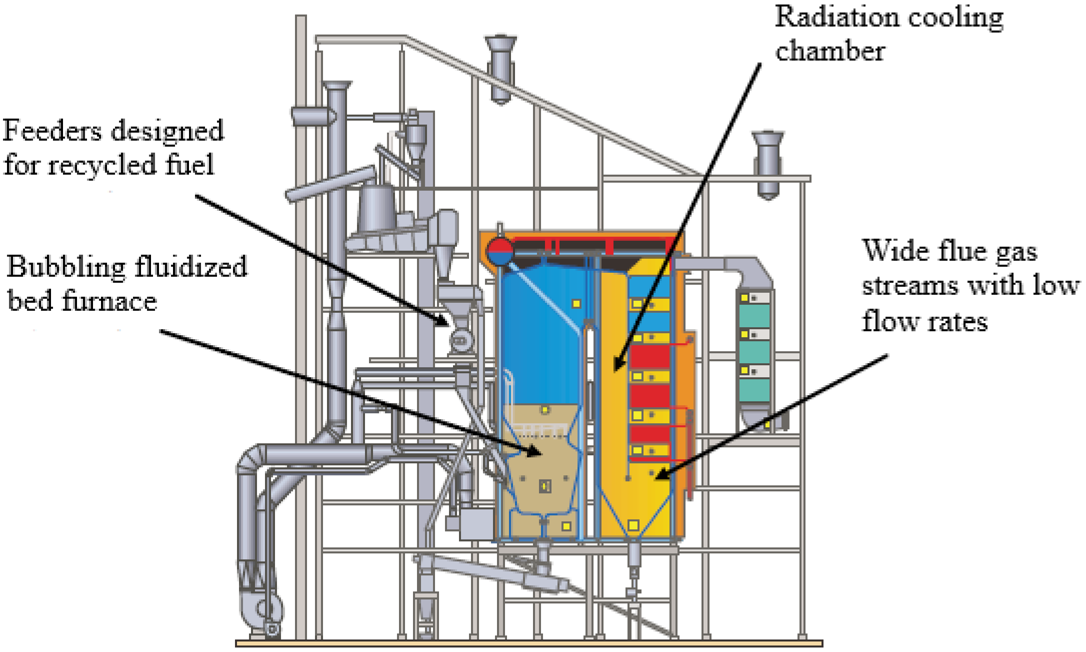


Figure 4. Basic structure of a combustion plant with BFB technology (Modified from: Vesanto 2006: 32).

Figure 4 indicates main parts in combustion plant with BFB technology. It shows waste drop horn, through which waste is fed into furnace. Figure shows also that flue gases are led through top of the furnace to radiation cooling chamber and further to large flue gas ducts.

The CFB technology is based on the BFB technology, so furnace operating principles are very similar. In a combustion plant with CFB technology, flow rate of flue gases is considerably higher, causing a bed material to pass a significant amount from the furnace with flue gas. The bed material is separated from the flue gases in a cyclone and returned to the furnace. Flue gases are passed from the cyclone to a boiler through the pre-cooling chamber, as well as in BFB technology.

Because mixing of fuel is more intensive in circulating fluidized bed, combustion is very efficient, and volume required by furnace is smaller compared to the BFB technology. For that reason, the CFB technology is used in larger combustion plants. Because of higher-pressure losses, the CFB technology own energy consumption is higher than that in the BFB technology combustion plant. The CFB technology is more suited to oxidizing fuels and waste due to its good material and heat transfer. Basic structure of a furnace with the CFB technology is shown in Figure 5. (Koornneef et al. 2006: 20–21; Vesanto 2006: 31–33; Spliethoff 2010: 221–222.)

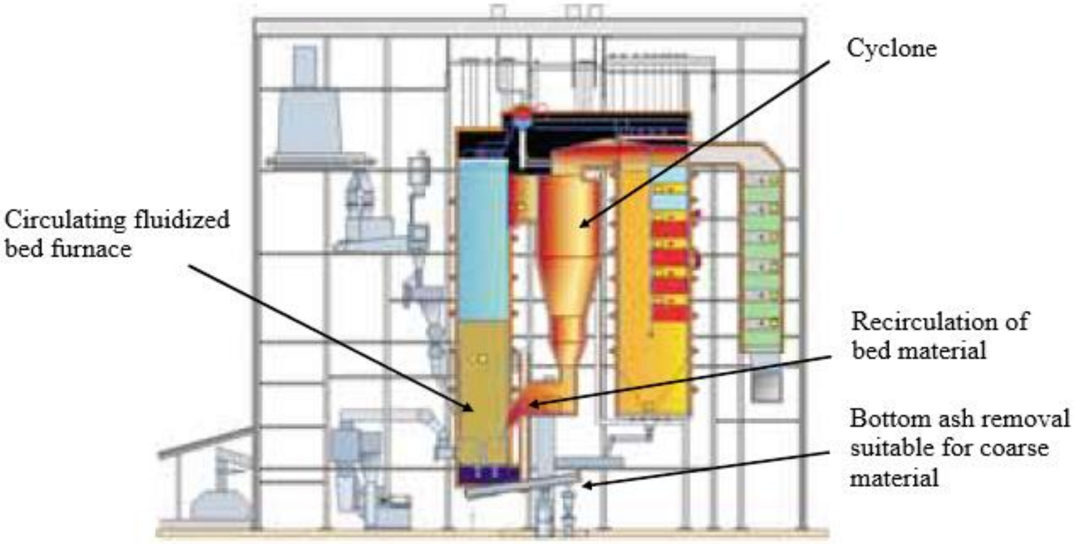


Figure 5. Basic structure of a combustion plant with CFB technology (Modified from: Vesanto 2006: 33).

Figure 5 presents structure of a combustion plant with CFB technology. Main difference with a combustion plant with BFB technology is cyclone, which through non-combustible material re-enters combustion cycle in CFB technology. This combustion plant includes also accordingly circulating fluidized bed, radiation cooling chamber and ash processing system as shown in Figure 5.

2.2 Technology of used waste incineration power plants

Waste incineration power plant is modular in this study, in other words the incineration power plant consists of modular incineration lines and the entire incineration power plant may have one to four incineration lines. The used waste incineration power plant has been implemented using the grate combustion technology. The waste incineration power plant used in the study includes five functional blocks:

1. waste incineration
2. heat radiation and cooling
3. waste heat recovery
4. air pollution control
5. power generation.

Each modular incineration line contains the required technology for operation. Figure 6 shows a principle of the used waste incineration power plant, where you can see different blocks of the incineration plant except for power generation. These blocks of incineration plant are discussed in more detail in Sections 2.2.1–2.2.5. (Poltto ja palaminen 2002: 466–467, Woima 2018a.)

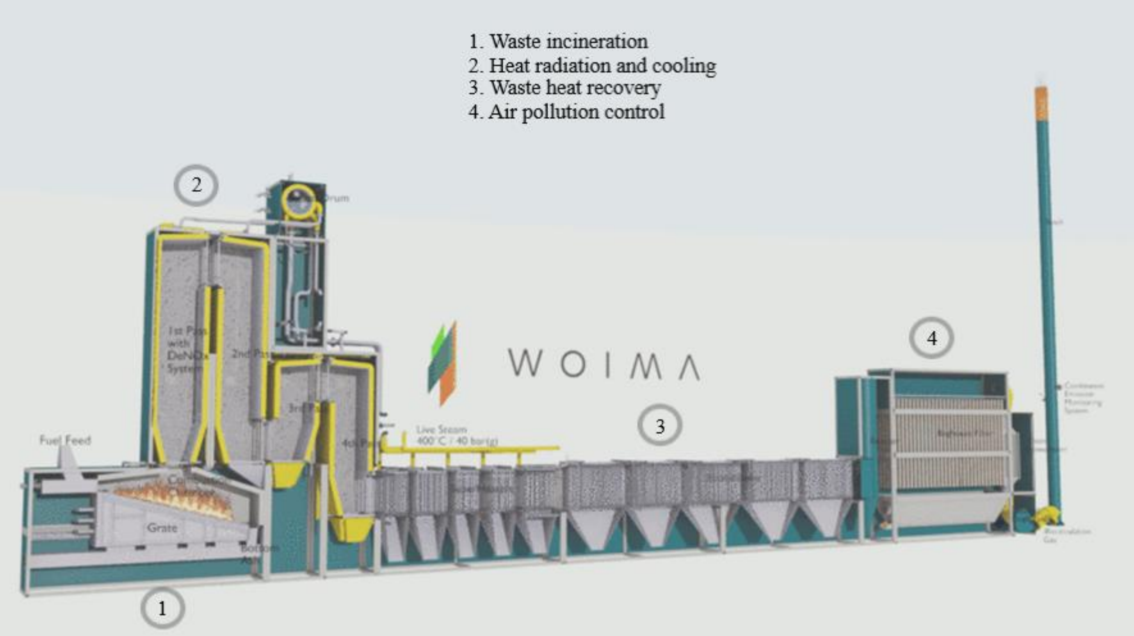


Figure 6. Operation principle of the modular waste incineration plant (Modified from: Woima 2018a).

2.2.1 Waste incineration

The first phase in the technology is waste incineration. Since the technology used in incineration is a grate technology, incinerated waste passes through the spinning phases at this phase. In practice, incinerated waste moves forward on a reciprocating grate and passes through the drying, pyrolysis and char combustion. After the incineration, a residue will form a bottom ash that eventually falls into a cooling pool. The incineration takes place completely with a primary air supplied to a grate. At the same time, the primary air also acts as a cooling material to the grate, which reduces a need for maintenance work.

Cooled bottom ash dropped into the cooling pool is carried to an ash treatment system. In the treatment system, excess water is removed and returned to the cooling pool. The bottom ash can be used for infrastructure construction or cement production. Alternatively, it can also be sealed to a landfill. (Woima 2018a.)

2.2.2 Heat radiation and cooling

After the waste incineration, follows a phase of heat radiation and cooling. Because of the waste incineration, there are gasified fractions that move to an adiabatic combustion chamber where they are burnt. To ensure complete combustion of the gases, the secondary and tertiary air are fed into the adiabatic combustion chamber. From the combustion chamber, gases flow into the radiation or cooling duct where steam as well as water in membrane wall piping absorbs heat of flue gas.

The flue gas contains toxic compounds, such as furans and dioxins, which are removed from the gas by combustion. A sufficiently long radiation duct after the combustion chamber ensures that these toxic compounds are fully burnt. The radiation duct also cools the flue gas transferred to a waste heat recovery boiler to avoid temperature corrosion. (Woima 2018a.)

2.2.3 Waste heat recovery

Waste heat recovery is carried out by recovery boiler. The recovery boiler is designed to collect remaining heat in the flue gas by convection. This requires the recovery boiler contained in superheater, evaporator, economizer and air preheater. The superheater and evaporator are needed to convert vapour formed in the radiation duct walls to the superheated saturated vapour. Purpose of the economizer is to preheat water flowing into a steam drum from a water tank. The air preheater is needed in turn to heat the primary, secondary and tertiary air to improve an efficiency of combustion.

The waste heat recovery efficiency is affected by fly ash in flue gas. Fly ash accumulates on the heat recovery boiler wall and piping over time and this reduces an efficiency of heat transfer. Therefore, soot must be removed regularly to maintain the process efficiently. (Woima 2018a.)

2.2.4 Air pollution control

Control of air pollution is based on a dry air pollution control (APC) system in the waste incineration power plant. The APC-system includes a reactor where flue gases are first directed. In a reactor, to flue gases are added impurity-binding chemicals, such as hydrated lime, potassium hydroxide and activated carbon. The reaction products are removed from the process into flue-gas stream mixed with dust. Dust is separated by a textile filter, which also acts as a chemically active purifier in the process. The process is dry, as the final product produces dry ash residue and does not produce effluent from the cleaning of flue gases which should be cleaned.

Bottom and fly ashes generated in the process are sufficiently clean and can be used, for instance, in road construction. Ash produced in the APC-system contains a relatively large proportion of heavy metals and other toxic substances and therefore needs to be dealt with in a separate process. Amount of bottom and fly ashes are together about 15 % and APC ash is about 3 % of the total amount of incinerated waste. (Westenergy 2013, Woima 2018a.)

2.2.5 Power generation

Power generation is done by the steam turbine and generator. Saturated and superheated steam (400 °C, 40 bar) is supplied to the steam turbine. The steam rotates the turbine whose rotating energy is passed through a gearbox to the generator. The generator ultimately turns rotational energy into electricity. The used steam is conducted to the condensing system where steam is converted back to water.

The power plant can be used to produce steam, electricity, heat or potable water, but output may also be a combination of the above. This enables the generation of energy in form that is needed. By utilizing this feature, power output can be balanced and generated in required form. (Woima 2018a.)

2.3 Capacity of the used waste incineration power plant

In a distributed waste incineration power plant is used modular waste incineration lines which allow combustion capacity to be matched to waste generated. Incineration capacity of one modular incineration line is 150–175 tons of waste per day. This amount of waste corresponds to an area with a population of about 200 000. Waste incineration power plant can generate steam, electricity or both electricity and heat. One modular incineration line is sufficient to generate steam of 17 tons. Electricity generation capacity is 3.4 MW (gross) and 2.7 MW (net). In combined heat and power (CHP) generation, the incineration line can generate 2 MW of electricity and 10 MW of thermal energy. Waste incineration power plant can contain one to four incineration lines. Waste incineration power plant with several incineration lines can incinerate more waste and generate more energy. (Woima 2018b, 2018c.)

It introduces that both waste incineration capacity and production capacity change proportionally to each other. Energy produced can be better utilized if energy can be produced as CHP and part of energy can be utilized as heat. In this case, electricity generation capacity is 2 MW, while it is only slightly larger, 2.7 MW in electricity generation. In addition to generating 2 MW of electricity, 10 MW of thermal energy can be produced.

Table 1 shows a capacity of a waste incineration power plant with different number of incineration lines. It introduces that both waste incineration capacity and production capacity change proportionally to each other. Energy produced can be better utilized if energy can be produced as CHP and part of energy can be utilized as heat. In this case, electricity generation capacity is 2 MW, while it is only slightly larger, 2.7 MW in electricity generation. In addition to generating 2 MW of electricity, 10 MW of thermal energy can be produced.

Table 1. Variations in incineration and power generation capacity of the waste incineration power plant used in the study. (Woima 2018b, 2018c.)

Variation type	**Number of incineration lines**			
	1	**2**	**3**	**4**
Waste incineration daily capacity (tons)	150–175	300–350	450–525	600–700
Options for daily power generation capacity:				
• steam (tons/h)	17	34	51	68
• electricity (net) (MW)	2.7	5.4	8.1	10.8
• combination of				
○ electricity (MW) and	2	4	6	8
○ thermal energy (MW)	10	20	30	40

3 DESIGNING A DISTRIBUTED WASTE INCINERATION POWER PLANT: STUDY CASE NAIROBI

Waste incineration power plant is distributed when there are several incineration power plant units and they are smaller. Size and number of incinerators can be decided on a project-by-project basis and this project involves six distributed incineration power plant units in Nairobi County. When designing the distributed power plant for Nairobi, in the study is considered that the used technology has already been developed and technology includes waste incinerator, residue systems, air pollution control systems and power generation system. In addition to technology, logistics factors are left out of this study. The design and implementation of the distributed incineration plant will therefore be the object of planning.

3.1 Implementation plan

When starting a distributed waste incineration project, project plan with project-related tasks is created. The project plan considers issues related to a construction of a waste incineration, waste management and recovery of power from waste incineration. Project design and implementation consists of the following steps:

- project location, size and population analysis
- waste management plans
- selection of waste incineration technology
- feasibility analysis
- project area design and layout
- technology required by the waste incineration power plant including solutions for waste incineration and flue gas cleaning
- construction of waste incineration power plants
- utilization of power output. (Rogoff & Screve 2011: 125–127; Pöyry 2018).

This study will include the above implementation phases, with the exception of waste management and logistics issues. When the waste incineration technology used has been selected and the related technology is presented in Chapter 2, the design of the project area is mapped.

The project focuses on the Nairobi County, located around the capital of Kenya. Size of the area is about 695 km^2 and population in the area is about 3.1 million (KNBS 2017: 17). In the Nairobi County produced waste about 2 500 tons per day in 2017. Based on the size and population of the region, in the Nairobi County are invested six distributed modular waste incinerators. In that case, the costs of transportation of waste and the management of waste will remain reasonable. Figure 7 shows population location in the Nairobi County. Population density is highest in the middle region and lower in peripheral areas.

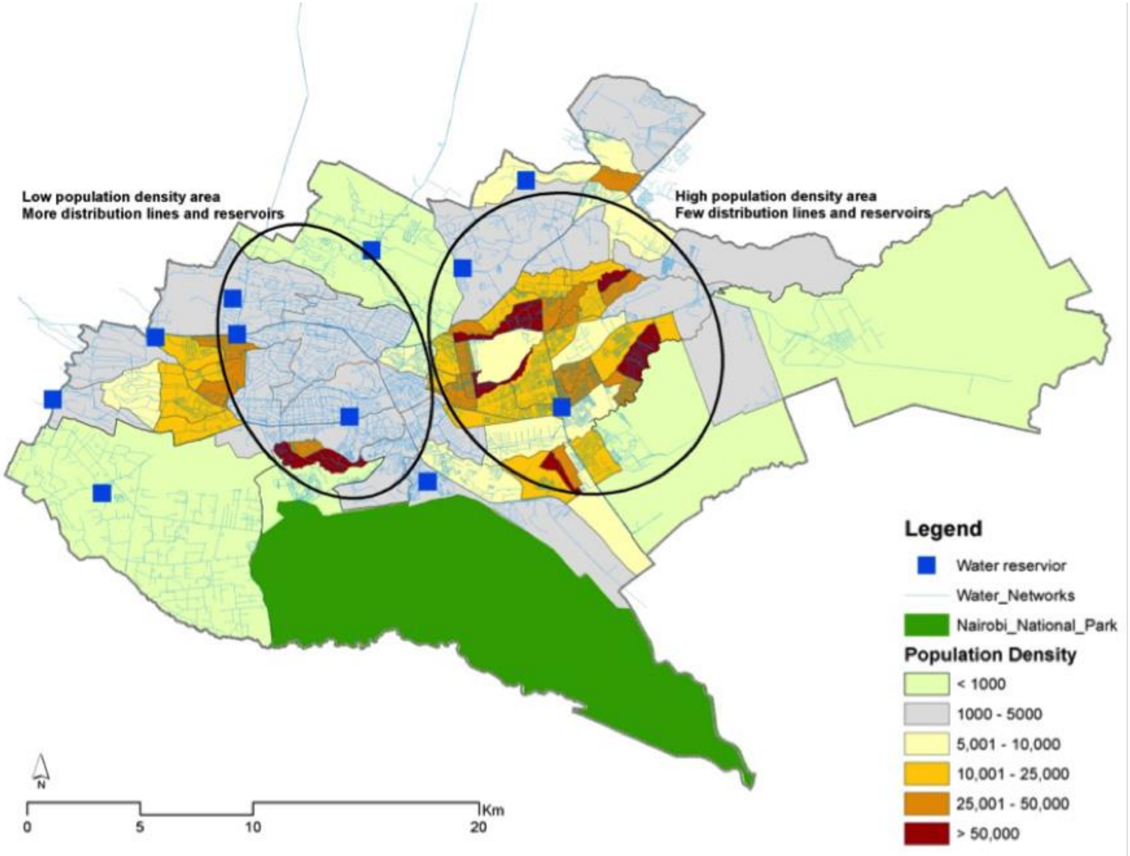


Figure 7. Population density in Nairobi County (Gora 2018).

Depending on the density of the regional population, suitable locations for waste incineration power plants are selected. The waste incineration power plants are placed evenly around the densely populated area so that the logistical costs associated with waste management remain as small as possible. In a suitable area, a free land area must be found for the waste incineration power plant where the incineration power plant can be located. Selected locations for waste incineration power plants are shown in Figure 8.

Figure 8. The locations of waste-to-energy power plants used in the study.

Required incineration capacity of each incineration power plant is determined by population around the incineration power plant and defined waste collection area. For each waste incineration power plant, an appropriate collection area is defined based on logistics. Capacity requirement of each incineration plant depends on amount of waste generated in the collection area. Amount of average available waste fuel in each waste incineration power plant based on amount of waste is shown in Table 2.

Table 2. Average available daily waste fuel of waste incineration power plants used in the study by region.

Waste incineration power plant	**Average available daily waste fuel (tons)**	**Number of needed incineration lines**
Power plant 1	463	3
Power plant 2	928	6
Power plant 3	333	2
Power plant 4	473	3
Power plant 5	439	3
Power plant 6	280	2
Total	*2 916*	*19*

Table 2 shows that waste fuel for each incineration power plant is about 300 to 500 tons per day apart from incineration plant 2, for which incinerated waste will be over 900 tons per day. The number of needed incineration lines shown in the table is calculated based on available waste fuel.

After the project area design is done, utilization of power output generated by incineration plant is next reviewed. Each waste incineration power plant can generate steam, electricity or electricity and heat. Energy can be generated as steam if there is a steam-utilizing industry near the incineration power plant. If there is no steam-utilizing industry near the incineration power plant, energy from the incineration can be generated as needed, either as electricity or combined with generation of electricity and heat. Also, power could be stored for example in fuels for transportation. (Rogoff & Screve 2011: 126–127).

3.2 Main requirements

The distributed waste incineration power plant requires sufficient space and some maintenance to stay in operation. Furthermore, operation has to ensure availability of waste fuel, electricity and water as well as delivery of flue gas cleaning chemicals. Also, ash produced by waste incineration has to also be recycled forward. (Rogoff & Screve 2011: 128.)

The power plant with four modular incineration lines requires less than 10 000 m^2 of land and the land requirement for power plant with pre-sorting system is about 13 000 m^2 of land. The land area should be located at least 50 m away from the nearest settlement due to the noise and smells caused by power plant. An ideal place for the power plant would be 20 000 m^2 plot near existing industry. The roads and power grid have been built for industrial use and the utilizers for energy fractions are near the power plant.

The operation of a waste incineration power plant requires a sufficient amount of available incinerated waste. The used waste fuel is received by collecting wastes from nearby area. The collection area is usually around the incineration power plant and size of area is affected by amount of waste generated in the area. The waste incineration power plant needs waste fuel as a steady flow, so a small waste storage site disposed near the incineration power plant is necessary.

The distributed waste incineration power plant needs electricity for some functions. Power plant generates 3.4 MW (gross) and 2.7 MW (net) electricity, so the own electricity consumption of the power plant corresponds to about 0.7 MW power. The power plant does not need external electricity because power plant can take the necessary electricity from electricity it generates, except for power plant start-up and shut-down. Waste incinerator to be considered for starting and shutting the power plant includes a generous diesel generator set. This diesel generator set can be used to operate belts and air blowers. (Woima 2018b.)

The waste incineration power plant requires a source of water for needs to be operation. Water is required in two subsequent stages after waste incineration. At following stage after waste incineration, water is needed to recover heat in flue gas. In this stage water need is about 0.5 m^3/h. Water or water vapour acts as a heat conductor that transfers heat to a recovery boiler. Also, in the waste heat recovery stage, water acts as a heat exchanger. Water is transferred from a radiation channel to the heat recovery boiler by convection. This stage requires more water, about 800 m^3/h. The process is open, so water used in the process returns back to nature. However, the process requires a rather large source of water, such as a river, lake or sea. (Rogoff & Screve 2011: 128; Woima 2018b.)

When cleaning flue gases, chemicals are used to bind contaminants from air. In case of waste incineration, this process is needed as chemicals for urea, lime and activated carbon. Urea is used to neutralize nitrogen oxides (NO_x) in flue gases. After removal of NO_x, the remaining hazardous compounds are bound by flue gases using lime and activated carbon to a textile filter. (Westenergy 2018.)

For ensuring operation of waste incineration power plant process control and monitoring system is needed. The system must be able to monitor the various functions of the waste incineration power plant, such as waste input and incineration processes. The system makes it possible to detect potential problems quickly, so that operation of the incineration power plant is as effective as possible. (Rogoff & Screve 2011: 128.)

3.3 Power generation capacity

Power generation capacity of waste incineration power plant is determined by number of waste incineration lines in the waste incineration power plant. According to Table 1, the waste incineration power plant can generate a specific amount of energy depending on its size. Accordingly, Table 3 illustrates daily power generation capacity of each power plant in alternative forms of energy in relation to the rated power.

Table 3. Alternative daily power generation capacity of each waste incineration power plant in relation to the rated power (Woima 2018c).

Waste incineration power plant	**Capacity (%)**	**Steam (tons/h)**	**Electricity (net) (MW)**	**Combination of electricity and thermal energy (CHP) generation**	
				Electricity (net) (MW)	**Thermal energy (net) (MW)**
Power plant 1	15.8	51	8.1	6	30
Power plant 2	31.6	102	16.2	12	60
Power plant 3	10.5	34	5.4	4	20
Power plant 4	15.8	51	8.1	6	30
Power plant 5	15.8	51	8.1	6	30
Power plant 6	10.5	34	5.4	4	20
Total	*100*	*323*	*51.3*	*38*	*190*

Table 3 shows that power plants 3 and 6 are the smallest and both cover 10.5 % of power generation capacity. Power plants 1, 4 and 5 are slightly larger and each capacity is 15.8 % of the total capacity. The largest of the power plants is power plant 2 with a double capacity compared to the power plants 1, 4 and 5. The capacity of incineration power plant is estimated by density of population in area because power generation capacity is determined by waste generated. Waste is generated according to population of the area.

Output power of the waste incineration power plant can be controlled either through waste incineration or power generation. The waste incineration can be controlled by a combustion control system comprising a waste feed system, a grate system and a combustion air system. In the power generation system, a form which power is generated, can be controlled.

With a waste feed system, magnitude of a waste stream supplied to the incineration plant can be controlled. Greater waste stream generally results in a higher output power, but size of waste stream also affects quality of incineration. Problem is that waste is a non-homogeneous fuel and its incineration time varies. In a furnace, incineration takes place at different stages and the furnace has at same time non-combustible, partly incinerated and residual char incinerated waste. For this reason, it is important that the waste feed system feeds in a proper amount of waste to the furnace. If there is too much waste in the furnace, waste does not burn fully in a previous stage before moving to a next incineration stage. The system maintains proper waste feed rate for waste incineration. In addition, auxiliary fuel can be used in the system to advance incineration if necessary. (Yufei, Yan, Zhongli & Keming 2008: 342–343; Vakkilainen 2017: 261–262.)

In the grate system, incineration can be controlled by the grate speed and waste layer thickness in the grate. In the grate incineration, speed of the grate regulates combustion of waste with the grate. The grate incineration involves four incineration stages, so combustion control also regulates other stages of incineration in the same ratio. Burning speeds is determined by a target steam flow according to:

$$S = \alpha \cdot \frac{Q_\mathrm{b}}{120} + \beta \ , \tag{1}$$

where Q_b is target steam flow as well as α and β are parameters whose values are adjusted during commissioning. Waste layer thickness affects a stability of an incineration. The incineration is stable when waste layer is not too thick but not too thin either. In a well-thick layer of waste, the drying of the waste and volatilization of combustion will probably be successful. The waste layer thickness should be adjusted according to heating value of waste. (Yufei et al. 2008: 343.)

Waste incineration can be controlled by a combustion air system in addition to the grate system. The combustion air system generally contains two to three different air inlets. Primary air is supplied to the furnace near the grate and is used to control combustion air ratio of the furnace. It is heated before feeding the furnace and the heated primary air removes moisture from waste and at same time, it cools also the grate. The heated primary air improves incineration, as incineration is enhanced by high-temperature primary air. (Yufei et al. 2008: 343–344.)

The secondary and possible tertiary air of the combustion air system are fed into the upper combustion chamber. The secondary air ensures complete incineration of waste above the grate. The possible tertiary air is used to incinerate gases generated during the incineration process. Combustion air flow F required for incineration can be calculated according to:

$$F = \alpha \cdot Q_b \cdot \frac{21}{21-O_2} + \beta - F_2 \,, \tag{2}$$

where Q_b is target steam flow, O_2 is oxygen content, F_2 is leak air flow and α, β are parameters whose values are adjusted during commissioning.

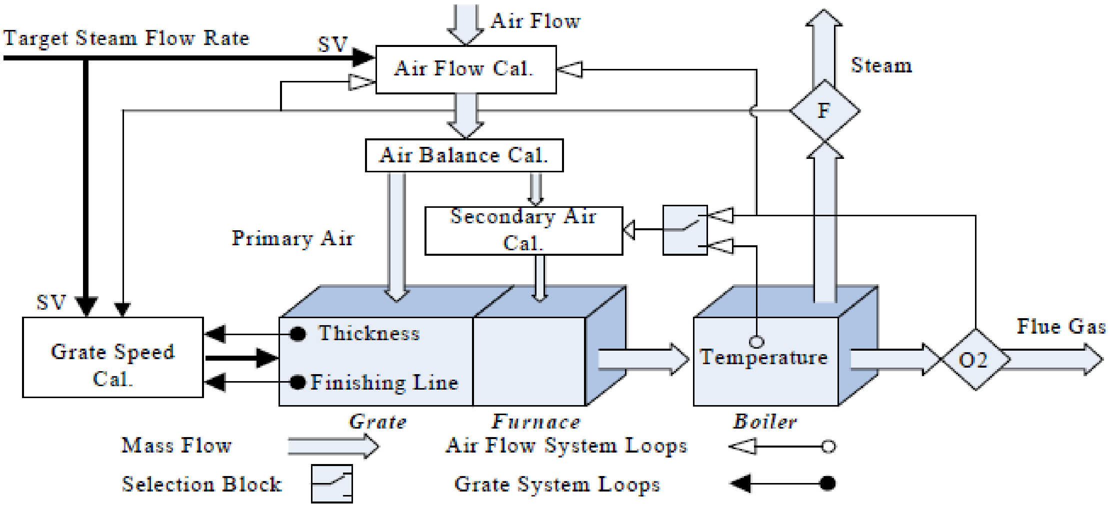


Figure 9. Combustion control system (Yufei et al. 2008: 342).

Figure 9 shows the principles of combustion control system. The target steam flow rate determines both grate speed and air flow. The grate speed is affected by deviation between the target steam flow rate and actual steam rate. In addition, waste layer thickness affects grate speed. The air flow is influenced by excess air ration in addition to the target steam flow rate. By air balance calculation, the air flow is divided into primary air and secondary air. The secondary air calculation is further made according to a boiler temperature. If the boiler temperature is high, the secondary air is used to control the boiler temperature. Otherwise, the secondary air controls the oxygen content. (Yufei et al. 2008: 344.)

An output of the waste incineration power plant is steam that can be used to power generation in different forms of energy. Generated energy can be directly utilized as steam, for example in industrial processes as process steam. This implies that a steam industrial power plant is located relatively close to a waste incineration power plant, as steam can be economically transferred only a few hundred meters.

Alternatively, steam can also be used for either heat or electricity generation or combined heat and power generation using a turbine generator set. Thermal energy can be recovered from hot steam coming to a turbine generator set by heat exchanger. Thermal energy can be moved several kilometres and can be used as heat energy for residential and industrial purposes in some industrial activities. Electricity is generated by directing hot steam to the turbine generator set. Hot steam rotates the turbine and the turbine further rotates the generating generator. Electricity is the most versatile of these forms of energy generation and is needed for many functions. The electricity generated by the waste incineration power plant can be supplied to an electricity grid and passed on to consumers.

The output of the waste incineration power plant can also be a combination of the above energy forms. If there is a process steam using industry near the waste incineration power plant, some of the energy can be generated as steam for industrial needs. The rest of energy can be used to electricity generation and also to thermal energy generation for house heating if necessary. (Woima 2018b.)

3.4 Costs of power generation

Cost of electricity (COE) generated at a waste incineration power plant is determined by two different cost items: capital and investment (C&I) costs of incinerator and operation and maintenance (O&M) costs of incinerator. Depending on a point of view, cost of fuel could also be included in the cost of electricity. However, this study focuses on the cost of electricity from point of view of electricity generation and therefore the cost of fuel is excluded from the scope. (Koornneef et al. 2006: 39.)

3.4.1 Capital and investment costs

The C&I costs include costs related to construction of a waste incineration power plant. The construction cost includes different functions of the power plant and Table 4 shows a breakdown of the costs of each system.

Table 4. Main cost components of the waste incineration power plant (Maisiri, van Dyke, de Kock & Krueger 2015).

Waste incineration power plant segment	**Main parts of segment**
Building	• civil works
Thermal processing equipment	• incineration unit • waste heat recovery system • water supply and treatment system
Air pollution control system	• flue gas treatment • ash processing
Power generation system	• turbine • generator
Other	

Building includes costs related to construction of incineration power plant, such as the grounding of the incineration power plant area and incinerator building. The building cost share is about 25 % of capital costs. Thermal process equipment is the largest capital cost of the incineration power plant and accounts for about 40 %. The thermal process equipment includes the incinerator and waste incineration systems. However, the flue gas and ash treatment processes are differentiated here and are part of air pollution control system. Its share is about 15 % of the capital cost. The reminder of the capital cost of the incineration power plant consists of a power generation system including the turbine and generator and other smaller cost components. They both account for about 10 %.

Table 5 shows a relative distribution of the cost of the waste incineration power plant to various functions as well as estimated costs of the functions for a waste power plant containing one furnace line.

Table 5. Relative distribution of the cost and the estimated C&I costs of the waste incineration energy power plant with one furnace line (Maisiri et al. 2015).

Waste incineration power plant segment	**Cost share (%)**	**Estimated C&I costs (M€)**
Building	25	3.8
Thermal processing equipment	40	6
Air pollution control system	15	2.3
Power generation system	10	1.5
Other	10	1.5
Total	*100*	*15*

Table 5 shows that most of the investment costs of the power plant are made up of thermal processing equipment, estimated 6 M€. This equipment includes, for example, the incineration unit. The other large share of investment cost constitutes air pollution control system which is about 2.3 M€. Most of this is the flue gas treatment. Several different components have to be cleaned from flue gases and this will increase the steps and the associated costs of flue gas cleaning.

Implementing a waste incineration power plant unit, C&I costs comprise also other implementation costs in addition to the power plant. Amount of these costs varies relatively on a case-by-case basis. These costs include at least the following costs:

- land required by the waste incineration power plant
- infrastructure
- waste handling machinery
- permission and implementation. (Schneider, Lončar & Bogdan 2010.)

3.4.2 Operation and maintenance costs

Operation and maintenance (O&M) costs include the costs associated with operating and maintaining the waste incineration power plant. The O&M costs are recurring, and their annual variation is relatively small. The following costs are typical for operation and maintenance:

- labour
- chemicals (urea, lime, activated carbon)
- equipment regular maintenance
- site and building maintenance
- periodic air emission testing
- ash disposal
- bag filter residue
- emission fees
- insurance
- financial expenses. (Schneider et al. 2010.)

4 FACTORS AFFECTING THE BALANCE BETWEEN POWER GENERATION AND CONSUMPTION IN NAIROBI

As stated in Section 3.1, population of Nairobi is about 3.1 million, in other words Nairobi is the densely populated area and energy consumption is relatively high. Because of limited capacity of the waste incineration power plants to generate energy, other energy sources are also needed to cover consumption in Nairobi. This chapter reviews aspects influencing balance between power generation and consumption.

4.1 Potential of existing energy generation in Kenya

In Nairobi, in the Embakasi area is located thermal power plant which is a gas turbine plant. Total effective capacity of the turbine is only 54 MW, which is not enough for consumption and this turbine will also be phased out in 2022 and 2024. Because there is no other energy generation in Nairobi, generation options have to be sought also in other regions of Kenya. (ERC 2016a: 70, 170.)

Kenya exploits many sources of energy for generating energy and currently uses both renewable and fossil energy sources. Efforts are being made to increase use of renewable energy sources (RES) while trying to abandon use of fossil energy sources. Nowadays, Kenya uses the following energy sources for energy production:

- hydropower
- fuel oil
- geothermal
- gas
- wind
- cogeneration
- biomass
- solar.

The total installed capacity of Kenya power generation is 2351 MW and relative distribution of the energy sources based on capacity is shown in Figure 10. Hydropower, fuel oil and geothermal energy comprise most of the Kenya energy generation capacity and cover about 95 % of installed capacity of Kenya. RES, hydropower and geothermal energy play an important role in energy generation, but wind power, solar energy and biomass still comprise very small part of generation capacity. (KPLC 2018: 205–207.)

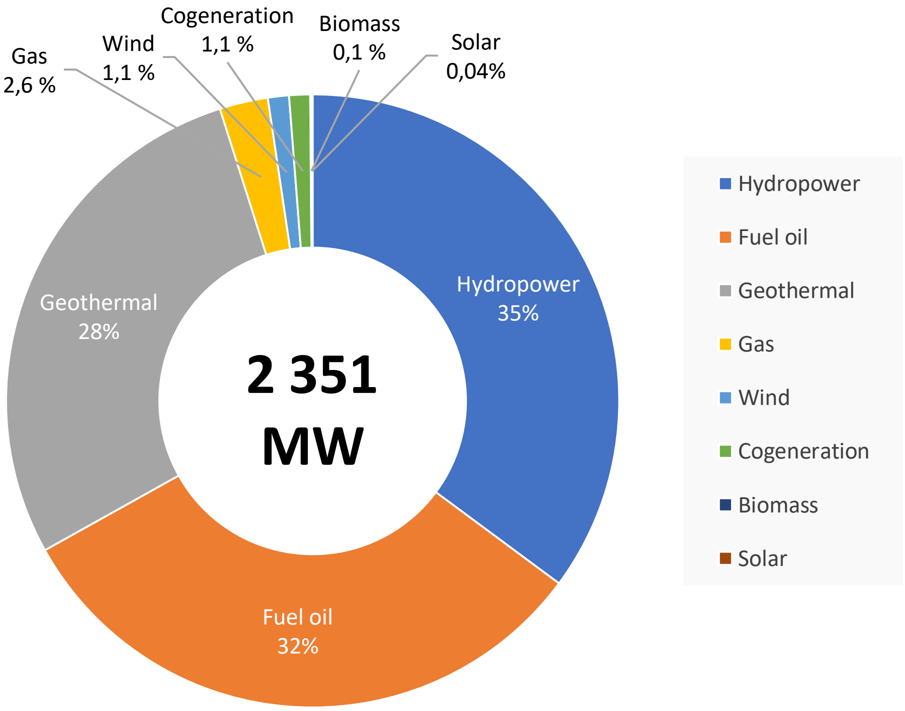


Figure 10. Relative distribution of energy sources in Kenya based on installed generation capacity at 30.6.2018. (KPLC 2018: 205–207.)

Produced energy in Kenya during the year 2018 was 10702 GWh, of which 171 GWh was imported. From the produced energy, system losses are 2244 GWh, which means that the generated net energy without the imported energy is 8287 GWh. System losses comprise then about 21 % of produced energy. Reducing the system losses can be increased the net energy generation. The produced energy for each energy source is shown in Figure 11. Compared to installed generation capacity, geothermal energy has now the highest energy generation when hydropower and fuel oil follow geothermal energy. (KPLC 2018: 208.)

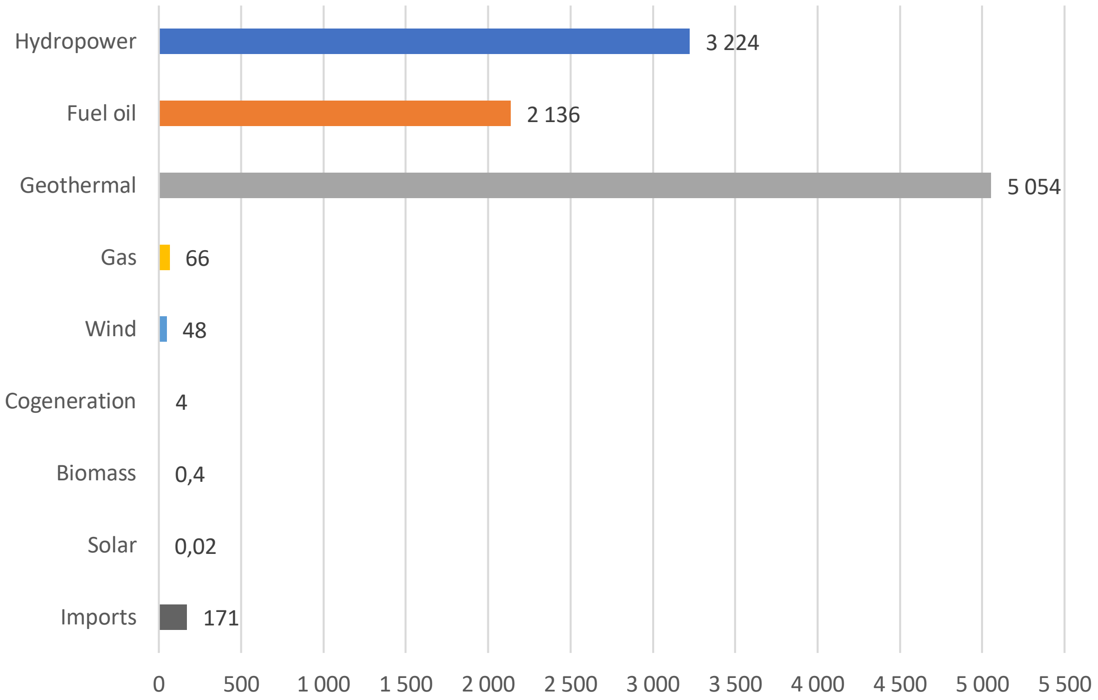


Figure 11. Purchased energy during 1.7.2017–30.6.2018 (KPLC 2018: 205–207.)

Kenya energy generation has two power generation companies that generate almost all generated energy. The bigger one is KenGen, which is leading electricity generating company in Kenya and accounts for about 70 % of power generation. The other is Independent Power Producers (IPPs), which generates almost rest of electricity. In addition to these, there is little offgrid capacity in power generation and electricity imports. Because KenGen is the only major power generation company, its own power plants are being evaluated. Figure 12 shows the power plants owned by KenGen. Figure presents also the gas turbine based thermal power plant located in the Embakasi area of Nairobi and it shows also other power plants near the Nairobi. Wind power, geothermal energy and hydropower appear near the Nairobi County. (KPLC 2018: 205–207.)

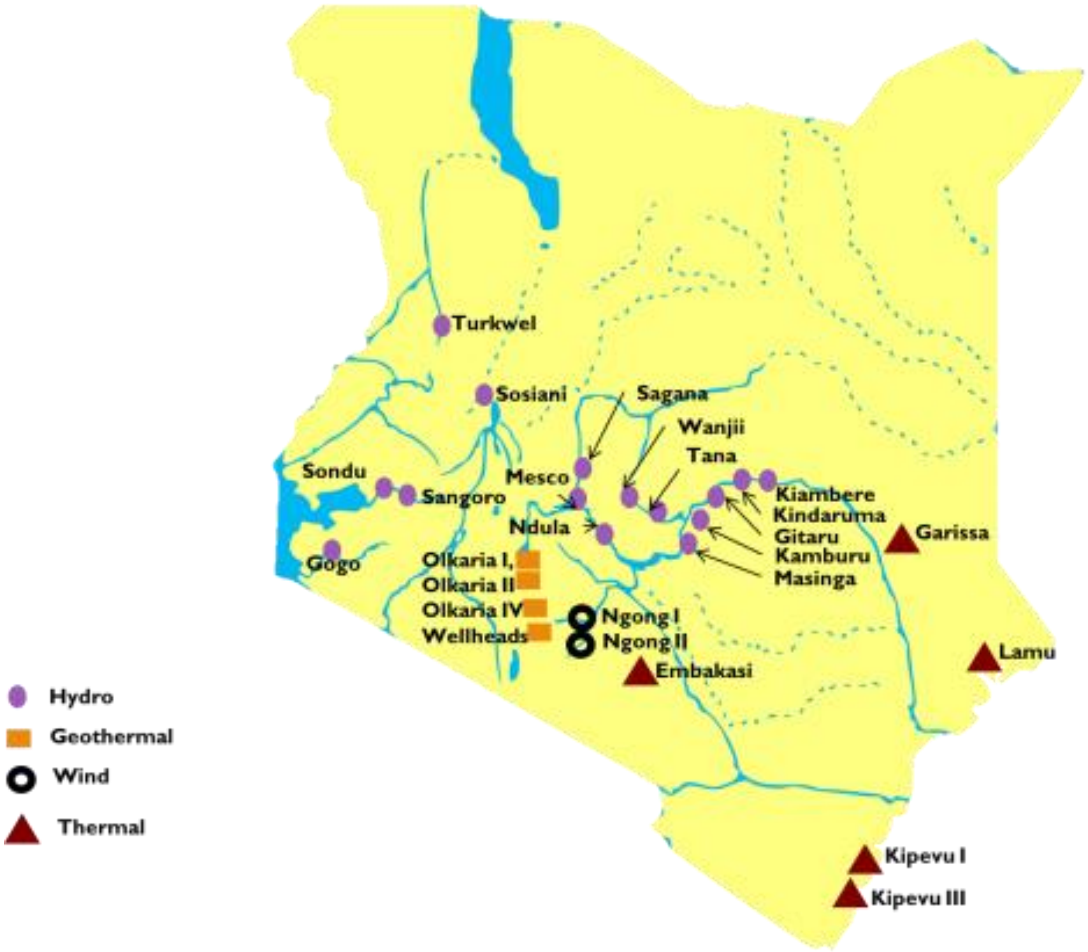


Figure 12. Power plants owned by KenGen (KenGen 2018).

Fuel oil covers a large part of energy generation in Kenya, but its share will decrease in future. Other fossil fuels, such as natural gas, are also still in use and there is a plan to replace them. According to the common goals set by the world, Kenia aims to abandon use of fossil fuels and to increase use of RES (ERC 2010). Kenya is already generating most of its energy with hydropower and geothermal energy, but fuel oil and other fossil fuels in use will be replaced by renewable energy. In addition, energy consumption is projected to increase significantly, which is why more energy needs to be generated. Figure 13 shows future scenario for energy generation and consumption. According to the scenario, electricity consumption and generation will increase almost fourfold from now to 2035. (ERC 2016a: 200–202.)

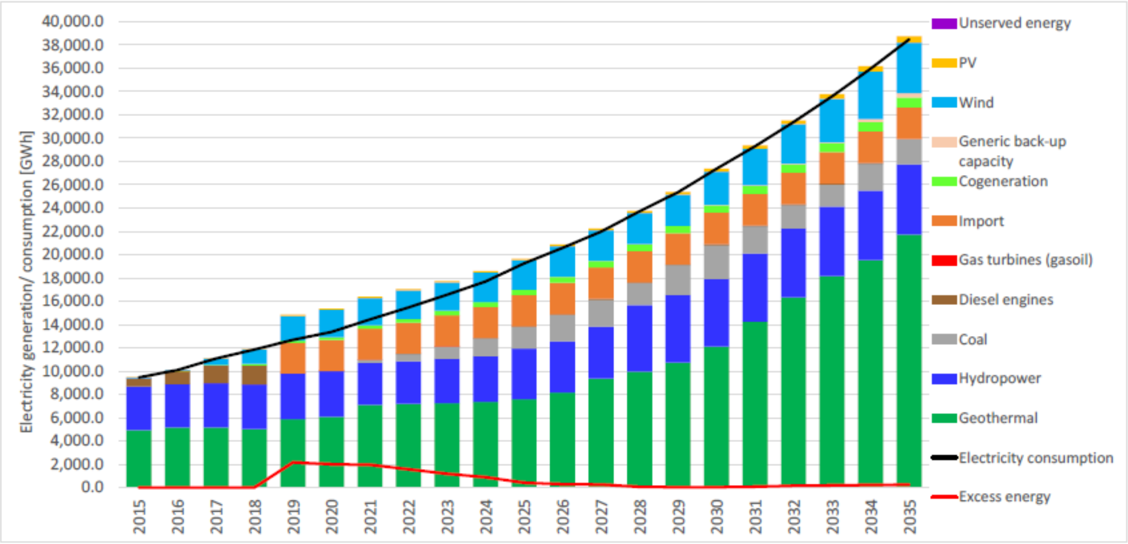


Figure 13. Reference expansion scenario – electricity generation versus electricity consumption (ERC 2016a: 204).

Hydropower is renewable energy and has played a major role in Kenya energy generation, but it will not grow considerably in future due to the problems caused by drought. The government of Kenya has decided to reduce dependence on hydropower due to drought. Kenya is located in the equator and has hot sunshine. Climate inside Kenya varies due to high altitude differences. Areas closer to sea surface are warm around a clock, causing drought. In higher areas, such as Nairobi, climate is more variable and there are also cooler periods. There are two rainy seasons in Kenya, from November to December and from March to May. (ERC 2016a: 69; Embassy of Finland 2016.)

Geothermal energy has also notable share in Kenya energy generation sector and Kenya is the largest producer of geothermal energy in Africa. Kenya will further continue to invest strongly in geothermal energy in future. According to Figure 13, the share of geothermal energy in energy generation will continue to be about half of the generated energy. (ERC 2016a: 69, 110.)

Regarding the fossil fuels, heavy fuel oil (HFO) and natural gas are not possible options for future energy generation, and they will be phased out by degrees. Use of HFO has negative environmental impacts and it is desirable to find a substitute, more environmentally friendly alternative to HFO for power plants. Natural gas is an environmentally better option to HFO, but because of its early stage of exploration, it is not a potential energy source for power generation. If enough natural gas is available, it could replace other fossil fuels in long term. However, liquefied natural gas (LNG) is considered an alternative source of energy, as there are huge resources of natural gas in Kenya. LNG enables diversification of fuels used in power generation and it has also environmental advantage relative to more harmful fossil fuels. (ERC 2016a: 101–103.)

Potential alternatives to renewable energy in Kenya contain wind energy, biomass and solar energy. At present, a contribution of wind power is very small but will grow in future. Problem with wind power generated energy is still wind fluctuation which influences amount of energy generation. Increasing use of biomass for energy generation can be potential alternative of renewable energy but it depends strongly on development in an agricultural sector. In the next few years, use of biomass is unlikely to increase remarkably in energy generation. (ERC 2016a: 114–117.)

Compared to wind energy and biomass, solar energy has a much greater potential in Kenya thanks to its geographical location. The total potential of solar energy in Kenya is several thousand times relative to the expected electricity demand in Kenya. Climate in Kenya is fairly stable and is located in the equator, which means that the solar energy generation does not change much during a year. Nevertheless, a share of solar energy in power generation will grow very slowly. (ERC 2016a: 118.)

For other energy sources, nuclear power can be considered as a possible alternative to energy generation. It is not renewable energy, but it is cleaner than energy generated by fossil fuels. Increasing the nuclear power requires relatively high investment costs, which makes it possible to increase it only in long term. (ERC 2016a: 121, 150.)

4.2 Demand side management

With higher power consumption, current power generation may not be sufficient to cover consumption. In that case, power generation can be balanced through power consumption. This can be used to help demand side management (DSM) and related techniques. The DSM means for example transferring electricity consumption from high load hours to low load hours. It can be used to reduce power consumption and to control loads. The DSM is mostly used the following techniques:

a) peak clipping
b) valley filling
c) strategic conservation
d) strategic load growth
e) load shifting
f) flexible load shape.

The effects of the above techniques are illustrated graphically in Figure 14. Peak clipping refers to load cutting during peak demand. Size and duration of the peak can be influenced by direct load control and consumer equipment. Valley filling aims to increase energy consumption during off-peak hours. As a tool, pricing is used when price of energy is cheaper during off-peak hours. Strategic conservation reduces seasonal energy consumption by exploiting consumption efficiency and energy waste. The opposite effect is achieved by a strategic load growth that directs seasonal energy consumption. Objective of the strategic load growth is achieved by using intelligent systems, energy efficient equipment and more competitive energy sources. Fifth technique of the DSM is a load shifting that shifts a part of demand from peak load period to off-peak load period. The latest technique is flexible load shape, which is an action and integrated planning between the licensee and consumer. (Macedo, Galo, de Almeida & de C. Lima 2014: 2–3; Gaur, Mehta, Khanna & Kaur 2017: 1.)

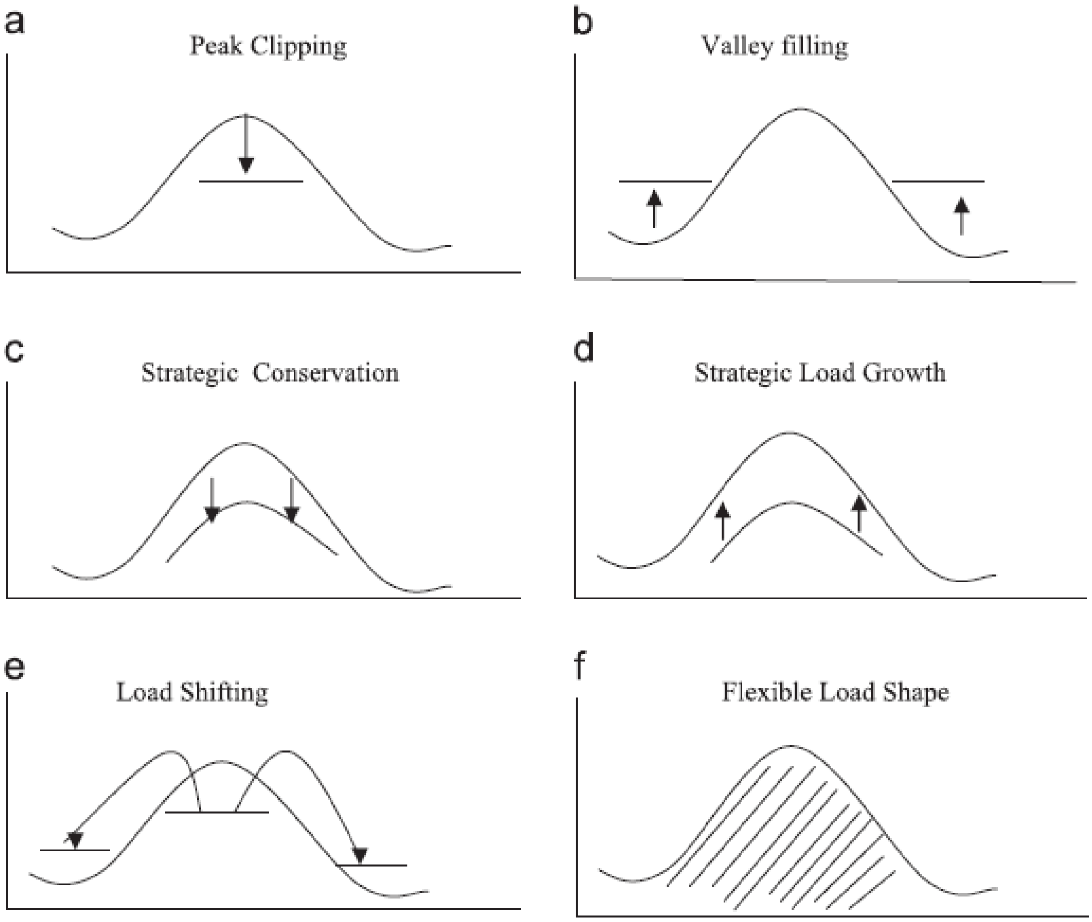


Figure 14. Graphic presentation of DSM techniques where loads are shown as a function of time. (Macedo et al. 2014: 3).

These DSM techniques can be utilized to manage demand flexibility in two different program packages: energy efficiency programs and demand response programs. The energy efficiency programs aim to reduce consumption by increasing energy efficiency, while the demand side programs affect consumption through incentives and pricing. Review on these two programs is next presented in Sections 4.2.1 and 4.2.2. (Paterakis, Erdinç & Catalão 2017: 3–4.)

4.2.1 Energy efficiency programs for DSM

At its simplest, energy efficiency (EE) means that using less energy to achieve same energy level (BGS 2019). It is a cost-effective way to meet growing energy needs. When energy consumption is increasing, only option is not to increase energy generation. Energy can be freed up by increasing the EE.

Figure 15 shows graphically effects of the EE program and it can be typical electricity load of facility. Figure indicates that with EE, load can be reduced over an entire consumption cycle. The EE programs can be further divided into two categories based on consumer behaviour. These are residential EE as well as commercial and industrial EE. The residential EE focuses on EE in housing and offers advice related to it. The commercial and industrial EE focuses correspondingly on EE of production and services. Because Nairobi is densely populated and there is little industrial activity, it is more profitable to focus on the residential EE. (McLean-Conner 2009: 71, 83.)

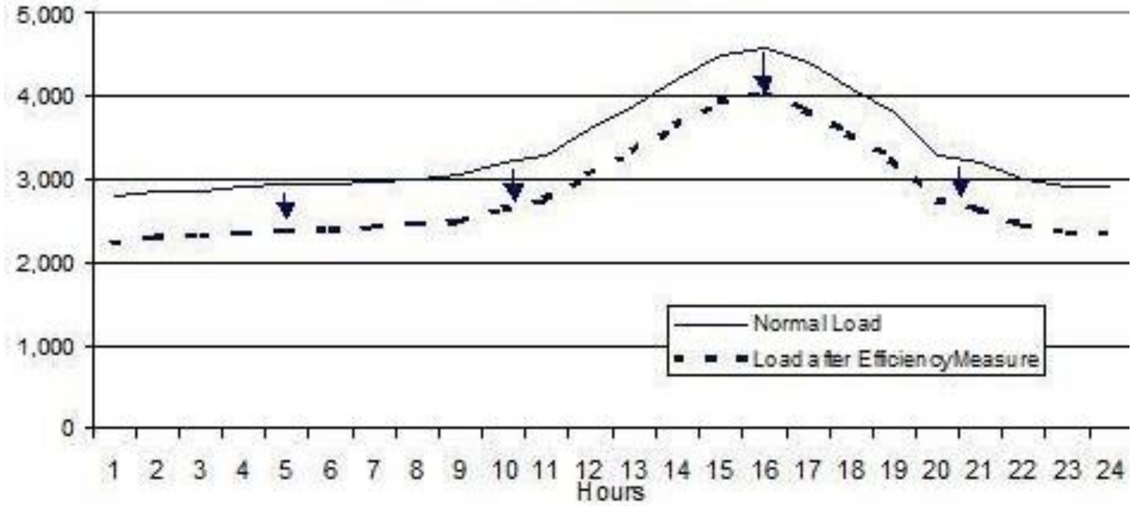


Figure 15. Effects of energy efficiency. The vertical axis represents the load in kilowatts and the horizontal axis the time of day in hours. (Energy Advantage 2017.)

Energy saving potentials of the residential EE include air conditioning (AC) system, entertainment, lightning, refrigeration and sanitary water. The biggest saving potentials of these are in lightning, refrigeration and sanitary water. On the commercial EE side, the biggest saving potentials are in office blocks, hotel and accommodation rooms as well as hospitals. These three subsectors construct more than 90 % of the commercial EE saving potentials. The industrial sector is very wide and its EE saving potentials consists of every industry. Additionally, the industry in the Nairobi County is very small, so the potential of the EE in the industry sector is not now useful. (ERC 2016b: 35, 46-47, 53.)

4.2.2 Demand response programs for DSM

Demand response (DR) means voluntary demand reduction and is used to control energy consumption outside consumption peaks. The DR can be divided into two main programs: incentive-based DR programs and price-based DR programs. Depending on an aspect, the incentive-based programs can be further divided into six different sections and price-based programs into three different sections as shown in Figure 16.

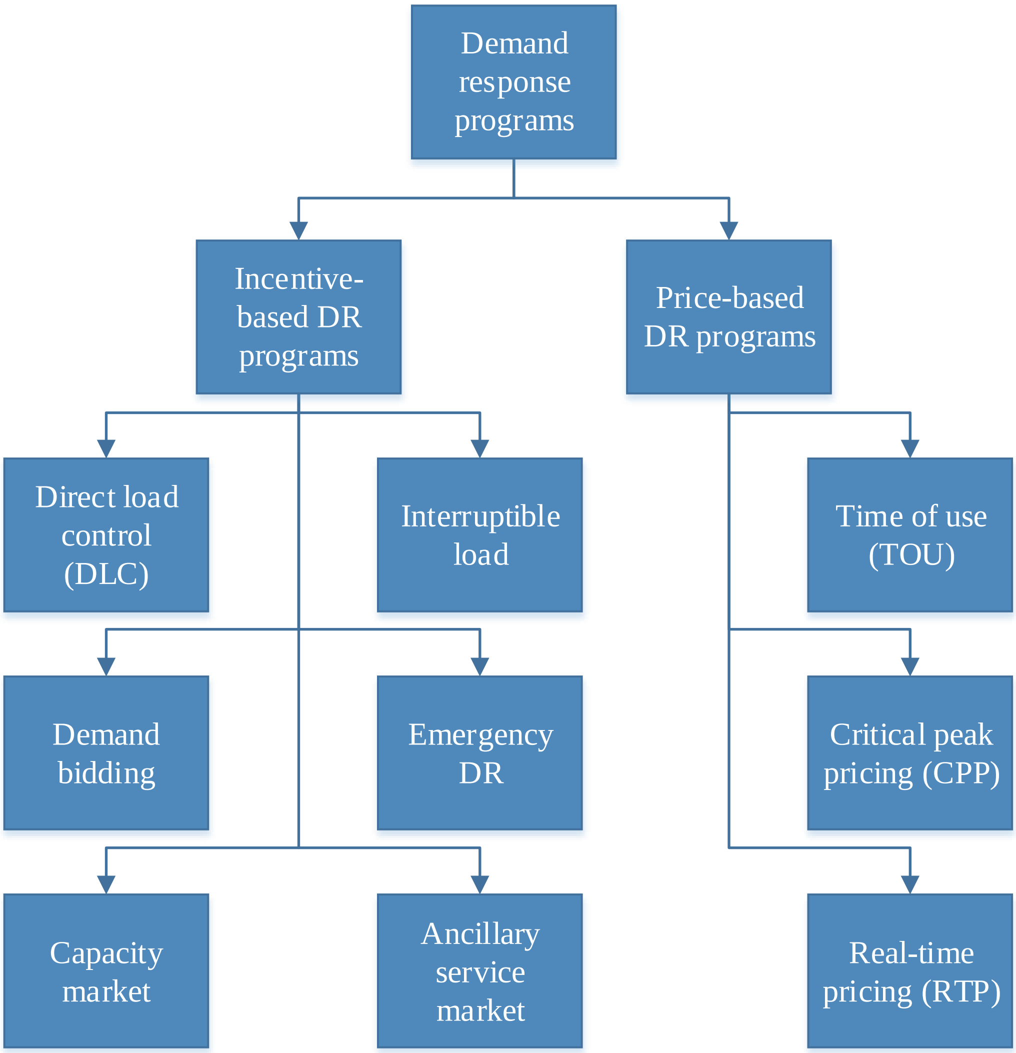


Figure 16. Classification of DR programs (Albadi & El-Saadany 2007; Jordehi 2019).

The incentive-based DR programs control direct energy consumption and energy-using loads. Two useable methods of the program in this study are direct load control (DLC) and interruptible load. The DLC is one of the most common methods of the incentive-based DR programs. It aims to control small consumers, such as residential and small commercial, energy use. The DLC can be implemented in practice, for example, by switching devices on or off. This is done for devices whose short-term interruption does not have a major impact. The effect of interruptible load is based on incentives for switching off certain loads. This technique is suitable for commercial and industrial use for medium and large consumers. (McLean-Conner 2009: 102; Mahin, Sakib, Zaman, Chowdhury & Shanto 2017; Paterakis et al. 2017.)

The price-based DR programs guide use of energy through pricing. These can be divided into three different programs: time of use (TOU), critical peak pricing (CPP) and real-time pricing (RTP). The TOU program utilizes variable electricity prices within a day. The day is typically divided into three time periods which are peak interval, mid-peak interval and off-peak interval. The price of electricity is the highest during the peak interval and the cheapest during the off-peak interval. The CPP is a variation of the TOU pricing and TOU prices are in use excepting certain peak load times when prices are significant high. The RTP is comparatively new program type which offers a real-time option for pricing. In this program, a customer pays for electricity according to a current price and pricing is implemented on a daily or hourly basis. (McLean-Conner 2009: 105–106; Paterakis et al. 2017; Jordehi 2019.)

Figure 17 represents Kenya indicative load curves within a day per region. Figure shows that the curves follow similar pattern regardless of a region. At night time, consumption is lower when consumptions in the commercial and industrial sectors are low. Then, principally air conditioning and other essential appliances consume electricity. Daytime, consumption of commercial and industrial activities increases consumption of electricity. In evening, commercial and industrial consumption will fall, but residential consumption will increase after office hours. Utilizing DR programs, a time-independent load in the Nairobi area could be transferred from evening to night. This would reduce the peak load and transfer load to a lower consumption period.

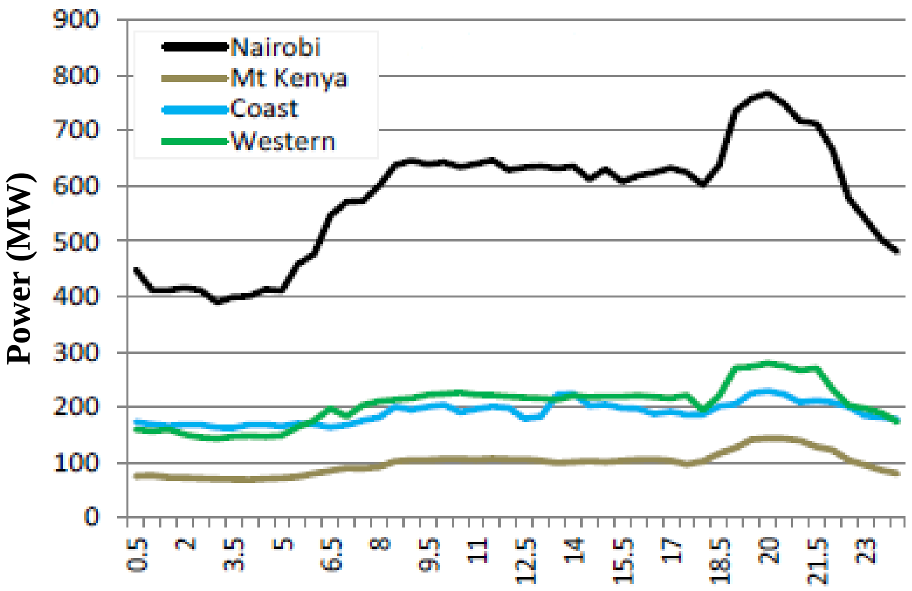


Figure 17. Load curves in regions of Kenya on 18.11.2014. The horizontal axis of figure presents hours of day and the vertical axis shows area load in megawatts. (ERC 2016a: 62.)

4.3 Energy storage technologies

Power generation cannot always be balanced by control of generation and demand side management. Capacities of waste incineration power plants are relatively constant, but power demand varies during a day. Generated energy must then be stored for later use if necessary. Waste incineration power plant can generate electricity, heat and steam. Several technologies can be used to storing electricity, and heat can be stored with a thermal energy storage. Following sections are reviews of storage techniques suitable for storing electricity and thermal energy.

4.3.1 Electrical energy storages

Electrical energy storage (EES) is used when electricity consumption and generation are not in balance and electricity needs to be stored. Using the EES is achieved several technical and financial benefits the most important of which are listed following:

- grid voltage support
- grid frequency support
- transient stability
- load levelling or peak shaving
- spinning reserve
- reliability
- ride through support
- unbalanced load compensation
- increasing penetration of RE sources
- cost reduction
- avoiding additional cost in generation
- avoiding additional cost in distribution. (Shawkat 2013: 87–89.)

Electrical energy can best be stored mechanically, electrochemically and electrically. These technologies include many options for storing electricity. Mechanical energy storages have higher storage capacity and discharge time, so they are better suited for high capacity storage applications compared to electromechanical and electrical energy storages. Due to shorter response time, the electromechanical and electrical energy storages are better suited to uninterruptible power supply (UPS) applications. Table 6 introduces commonly used technologies and summarizes technical characteristics of these categories. (Ibrahim, Ilinca & Perron 2007: 23–24; Palizban & Kauhaniemi 2016: 3–5.)

Table 6. Technical characteristics of electrical energy storage (EES) systems (Modified from: Shawkat 2013: 86; Zakeri & Syri 2014: 592; Palizban & Kauhaniemi 2016: 255).

EES technology				**Capacity (MWh)**	**Power (MW)**	**Response time**	**Discharge time**	**Life time (years)**	**Efficiency (%)**
Mechanical	PHS	small		≤ 5000	≤ 500	sec ~ min	6 ~ 24 h	≤ 70	≤ 85
		large		≤ 14000	≤ 1400	sec ~ min			
	CAES	under-ground	small	≤ 1100	≤ 135	≤ 15 min	≤ 8 h	≤ 40	≤ 85
			large	≤ 2700	≤ 135	≤ 15 min	≤ 20 h		
		above ground		≤ 250	≤ 50	≤ 15 min	≤ 5 h		
	FES			≤ 10	≤ 20	≤ 10 ms	≤ 1 h	≤ 20	≤ 85
Electrochemical	Lead-acid			0.25 ~ 50	≤ 100	millisecond	≤ 4 h	≤ 20	≤ 85
	Lithium-ion			0.25 ~ 25	≤ 100		≤ 1 h	≤ 15	≤ 90
	NaS			≤ 300	≤ 50		≤ 6 h	≤ 15	≤ 80
Electrical	SCES			≤ 0.3	≤ 0,3	≤ 10 ms	≤ 1 h	≤ 20	≤ 95
	SMES			1 ~ 3	≤ 10	≤ 10 ms	≤ 1 min	≤ 40	≤ 95

Pumped hydroelectric storage (PHS) stores energy into potential energy of water by pumping from a lower reservoir to an upper reservoir. When stored energy is to be used from energy storage, water is released from the upper water reservoir through the turbine back to the lower reservoir. Power capacity of PHS (P_{PHS}) can be calculated by means of water flow rate (Q_{w}) and fall height (h) when generating efficiency is known:

$$P_{\mathrm{PHS}} = \eta \rho g Q_{\mathrm{w}} h, \tag{3}$$

where η is generation efficiency, ρ is water density, g is gravitational constant, Q_w is water flow rate and h is height of fall. Storage capacity of PHS (S_PHS) can still be calculated when draining and filling water volume is known by

$$S_{\mathrm{PHS}} = \frac{\eta \rho g V h}{3.6 \cdot 10^{9}}, \tag{4}$$

where V is volume of water daily draining and filling. (Shawkat 2013: 83.)

Compressed air energy storage (CAES) is a large-scale EES technology and stores energy using compressed air. It consists of a drive motor which used for driving the compressor, high-pressure and low-pressure turbines as well as generator. The CAES can be implemented with either a diabatic or an advanced adiabatic storage system, and of these, the diabatic system is more commonly used commercially. The large-scale energy storage can be accomplished by an underground CAES, but a small-scale energy storage can also be accomplished by an above ground CAES. The above ground CAES has generally a higher cost compared to the underground CAES, but project implementation is easier. (Shawkat 2013: 81; Zakeri & Syri 2014: 9–10.)

Flywheel energy storage (FES) stores energy in form of mechanical kinetic energy. The flywheel is commonly used for storing energy in power systems. Energy (E) stored in the flywheel depends on a moment of inertia (J) of a rotor and a square of a rotational velocity (ω) of the flywheel:

$$E = \frac{1}{2} J \omega^{2}, \tag{5}$$

where the moment of inertia (J) can be calculated as follows:

$$J = \frac{r^{2} m h}{2}, \tag{6}$$

where r is radius, m is mass and h is length or height. (Shawkat 2013: 81.)

Battery energy storage system (BESS) is an example of the EES where energy is stored electrochemically. The BESS is one of the most cost-effective existing electrochemical energy storage technologies. Batteries are charged by internal chemical reaction when potential is applied to a terminal. They are respectively discharged by inverse chemical reaction. There are several different technologies for batteries, for example lead-acid, nickel-metal hydride (Ni-MH) and lithium-ion (Li-ion) batteries. (Shawkat 2013: 79–80.)

Super capacitors energy storage (SCES) operation is based on use of capacitors. Stored charge (q) in a super capacitor can be calculated

$$q = CU_{\mathrm{C}}, \tag{7}$$

where C is capacitance and U_{C} is voltage between capacitor plates. Capacitance (C) is defined

$$C = \frac{\varepsilon A}{d}, \tag{8}$$

where A is area of capacitor plates, d is distance between capacitor plates and ε is permittivity of dielectric. Energy stored in the capacitor plates (E) is obtained

$$E = \frac{1}{2} C {U_{\mathrm{C}}}^{2}. \tag{9}$$

Total voltage change of capacitor ($\mathrm{d}V/\mathrm{d}t$) when charging or discharging capacitor can be calculated as follows:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \frac{i}{C_{\mathrm{tot}}} + \frac{i \cdot R_{\mathrm{tot}}}{\mathrm{d}t}, \tag{10}$$

where i is circuit current, C_{tot} is total capacitance and R_{tot} is equivalent series total resistance. (Ter-Gazarian 2011: 151–152; Shawkat 2013: 80–81.)

Superconducting magnetic energy storage (SMES) is based on a magnetic field generated by an electric current and it exploits direct current (DC) field to generate magnetic field where energy is storage. Energy stored in the SMES system can be calculated

$$E = \frac{1}{2} L I^2, \tag{11}$$

where L is inductance of a coil and I is DC current flowing through the coil. The stored energy is used to calculate a rated power P

$$P = \frac{\mathrm{d}E}{\mathrm{d}t} = L I \frac{\mathrm{d}I}{\mathrm{d}t} = U_\mathrm{L} I, \tag{12}$$

where U_L is a voltage generated across the coil. (Shawkat 2013: 80.)

When choosing a type of energy storage system (ESS), energy storage costs are a key factor. These costs vary considerably between storage technologies. Summary of the costs of the various ESS is shown in Table 7. It shows that power-related costs in large-scale EES forms such as the PHS and CAES are high as they have high investment costs. However, their storage capacity is high, resulting in low energy-related costs. The biggest energy related costs are with FES and SCES. Power capacity costs vary depending on capacity, and for the large-scale EES, cost is generally lower and for small-scale EES, cost is higher. (Connolly 2010: 65–69; EIA 2018.)

Table 7. Cost of various ESS (Modified from: Shawkat 2013: 91).

Storage technology	**Power-related cost ($/kW)**	**Energy-related cost ($/kWh)**	**Power capacity cost ($/kW)**
PHS	600–2 000	0–20	5–100
CAES	425–480	3–10	2–50
FES	350	500–25 000	300–25 000
Lead-acid	200–580	175–250	50–400
Lithium-ion	-	900–1 300	600–2 500
NaS	259–810	245	300–500
SCES	300	20 000–82 000	300–2 000
SMES	300	2 000	1 000–10 000

4.3.2 Thermal energy storages

Thermal energy storage (TES) stores energy as heat for later use. It can counterbalance a mismatch between thermal energy generation and consumption and can achieve the following benefits:

- increase generation capacity
- enable better operation of cogeneration plants
- shift energy purchases to low-cost periods
- increase system reliability
- integration with other functions. (Dincer & Rosen 2011: 89–90.)

Storage of thermal energy is based on the appropriate thermophysical properties of TES materials. These include a favourable melting point for a thermal application, high latent heat, high specific heat and high thermal conductivity. Based on these features, there are generally three different types of TES in use: sensible heat storage, latent heat storage and thermochemical energy storage. (Alva, Lin & Fang 2017.)

The sensible heat storage is based on changing a temperature of a storage medium. Amount of energy supplied to the TES is proportional to a difference between the final and initial temperatures, a mass of the storage medium and its thermal capacity. The storage material in the sensible heat storage can be water, air, oil, rock beds, bricks, sand or soil. Choice of material is influenced by different properties such as density, specific heat, thermal conductivity, diffusivity, vapour pressure, chemical stability as well as compatibility with container material. Amount of heat stored in the sensible heat storage can be calculated

$$Q_\mathrm{t} = mc_p\Delta T = \rho c_p V\Delta T \;, \tag{13}$$

where ρ is a density of material, c_p is specific heat of storage material, V is a volume of storage material and ΔT is a temperature change in heat storage. (Dincer & Rosen 2011: 109–110; Capeza 2015: 3–4.)

The latent heat storage is based on a phase change in a storage material in which thermal energy is stored. In this storage system is usually utilized solid-liquid phase change. After melting a material, heat is transferred to the material and large amounts of heat storing at constant temperature. The stored heat is released when the material solidifies again. The storage materials used in the latent heat storage are, for example, water, paraffin, salt hydrates and salt. Heat stored in a latent heat storage is calculated

$$Q = mL \;, \tag{14}$$

where m is a mass of a storage material and L is a specific latent heat. (Capeza 2015: 4–6; Alva et al. 2017.)

Thermochemical energy storage uses chemical reactions with high energy to store energy. In storage process can be used a reversible reaction because products of the reaction should be able to be stored and retrieved when the reverse reaction occurs. Thermochemical energy storage can be divided between chemical reactions and sorption systems. Chemical reactions are used materials with high energy storage density and reversibility and finding appropriate materials is challenging. The most commonly used reactions are for instance carbonation reaction, ammonia decomposition and metal oxidation reactions. The sorption systems can be further divided to closed and open storage systems. In the closed storage system, a heat exchanger is used for heat transfer. Heat must be transported to an absorber while it is extracted from a condenser. In the open storage system, air is used to transport water vapor and heat between the adsorbent and system. Two reverse processes in system transfer heat to storage. The desorption process desorbs water from adsorbent by means of hot air, which results in the system cooling and saturating. The adsorption process adsorbs water vapor and releases heat when humidified cold air enters the adsorbent. (Capeza 2015: 7–8.)

Table 8 compares these three TES systems. In terms of capacity, the thermochemical energy storage is the best solution for large-scale thermal energy storage. The sensible heat storage has though a higher power range compared to the latent heat storage and the thermochemical energy storage. The cost of the thermochemical energy storage can be significantly higher than the other two options.

Table 8. Comparison of TES (Modified from: Sarbu 2017).

TES System	**Capacity (kWh)**	**Power (MW)**	**Efficiency (%)**	**Storage period**	**Cost ($/kWh)**
Sensible heat storage	10–50	0.001–10	50–90	days or months	0.1–10
Latent heat storage	50–150	0.001–1	75–90	hours or months	10–50
Thermochemical energy storage	120–250	0.01–1	75–100	hours or days	8–100

5 SIMULATION AND OPTIMIZATION OF POWER GENERATION

One of the main objectives of this thesis is to create a cost calculation model which can also be exploited in later projects. The cost calculation model is combined with simulation and optimization using *Homer micropower optimization model*. This chapter views a development of a simulation model as well as simulation and optimizations in two modes. Optimization in this work is based on the Homer optimization program and optimization means looking for the best simulations result based on defined criteria.

Homer optimization program is software originally developed at the National Renewable Energy Laboratory (NREL) and enhanced subsequently by Homer Energy. Homer is the software designed to be used for micropower optimization and optimization tool can be used in both electric power and thermal energy modelling. Several renewable and non-renewable energy sources can be used in simulations. Renewable energy sources especially solar photovoltaic and wind turbines well suited for use with Homer software. In addition, a model has a choice of different energy storages.

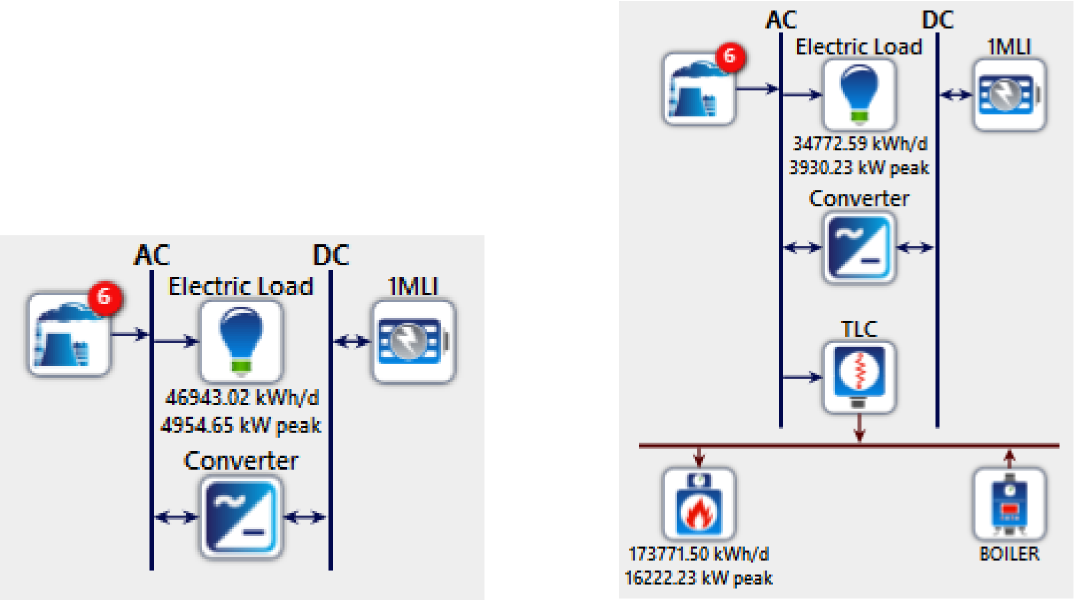
Homer has three important features to use: simulation, optimization and sensitivity analysis. The simulation is a necessary feature for optimization and sensitivity analyses. Simulation creates for any combination of components which meet the criteria. In practice, this means that if the simulation model contains an energy storage, the simulation will be performed with and without energy storage model, if possible.

Optimization phase follows simulation. In Homer, optimization means sorting and filtering systems obtained in simulation phase according to defined criteria. The criterion used for optimization can often be a total cost of a system used in the simulation over its life cycle, but it may also be another factor if desired. The last step is sensitivity analysis, which is not a mandatory step. At this stage, effects of uncontrolled variables on the system can be modelled, for instance, effect of wind speed on a system containing a wind turbine. (Homer Energy 2018a.)

Subject of this thesis is related to the distributed waste incineration power plant and simulation program is used for cost simulation and optimization. In Section 5.1 is first created a simulation model for both electricity generation and combined heat and power (CHP) generation. Next, simulations are performed which result in a cost calculation that includes, for example, system life cycle costs and annual operating costs.

5.1 Development of simulation model

As stated at the introduction used program is a micropower size optimization tool and model is limited to waste incineration power plants and other energy generation in Nairobi is ignored. In this case, the loads to be used are also proportional to the energy generated by the waste incineration power plants. The waste incineration power plants generate electricity or thermal energy if needed, so they can be modelled using conventional diesel engines. Also waste fuel is described in simulations with regular diesel fuel, so price of waste fuel is therefore the price of diesel fuel. Simulation model has key components only and thus it includes generators describing waste incineration power plants, an electric load, an electrical energy storage (EES) and its converter. In addition, the CHP generation optimization model includes a thermal load controller, a thermal load and a boiler. The distributed electricity and CHP generation optimization models are shown in Figure 18. (Homer Energy 2018b.)



(a) (b)

Figure 18. Models for distributed electricity generation (a) and CHP generation (b) used in simulations and optimizations.

Capital, replacement and O&M costs are included for generators, electrical energy storages and converters in the models. At the beginning of a new project, program uses the capital costs for these components. However, each component has a lifetime, after which the component is replaced by a new one and then a replacement cost is applied. The project lifetime created by Homer is defined as 50 years, close to maximum lifetime of this type of waste incineration power plant. Lifetime of the components of the model is as follows:

- 30 years for waste incineration power plant
- 10 years for electrical energy storage
- 20 years for converter.

Simulations are typically for a time period of one year, 8760 hours. These waste incineration power plants require annual maintenance, which takes about one month per year.

Annual maintenance can be placed at any time of the year, but in the simulations, maintenance is set to December. Hence, simulation time is from January to end of November in other words 334 days or 8016 hours.

Table 9 shows generation capacities of six power plants which are used in modelling. The generation capacities are introduced for both mode 1 where power is generated as electricity and for mode 2 where power is generated as CHP. In Table 9, for CHP generation, electricity generation capacity and thermal energy capacity have been calculated separately and finally their combined capacity has been added up. Annual generation capacity describes how much incineration power plant can generate energy in megawatts per year. This takes into account an annual maintenance, in other words in Table 9 the annual generation capacities are in practice 11 months generation capacity.

Table 9. Annual generation capacity of waste incineration power plants for electricity and CHP generation in relation to the rated power.

Power plant	**Mode 1: Electricity generation (MW)**	**Mode 2: CHP generation**		**Total CHP generation (MW)**
		Electricity (MW)	**Thermal energy (MW)**	
Power plant 1	2 705.4	2 004	10 020	12 024
Power plant 2	5 410.8	4 008	20 040	24 048
Power plant 3	1 803.6	1 336	6 680	8 016
Power plant 4	2 705.4	2 004	10 020	12 024
Power plant 5	2 705.4	2 004	10 020	12 024
Power plant 6	1 803.6	1 336	6 680	8 016

Table 10 presents costs of generators used in the model. Capital costs are cost of building a power plant and depend on size of the power plant. The age of power plant is expected to be 30 years, after which a part of the power plant has to be renewed and the replacement costs of the plant apply. Operation and maintenance (O&M) costs in the table are per year and recurring annually.

Table 10. Costs of waste incineration power plants used in modelling.

Waste incineration power plant	**Capital costs (M$)**	**Replacement costs (M$)**	**O&M costs (M$/year)**
Power plant 1	51.48	46.33	1.7
Power plant 2	102.96	92.66	2.3
Power plant 3	34.32	30.89	1.7
Power plant 4	51.48	46.33	1.7
Power plant 5	51.48	46.33	1.7
Power plant 6	34.32	30.89	1.7

Size of an electric load, which is used in the model, is dimensioned according to the total power generated by the power plants. According to Table 3, daily electricity generation of the power plants totals 51.3 MW, which is an average of approximately 2.14 MW per hour. In the CHP generation, daily electricity generation is 38 MW, which is average about 1.58 MW per hour. A load in the pilot city consists mainly of load in residential area, where load at night time is lower and in evening is higher than the average value. Daily load profile of the electric load used in mode 1 is shown in Figure 19.

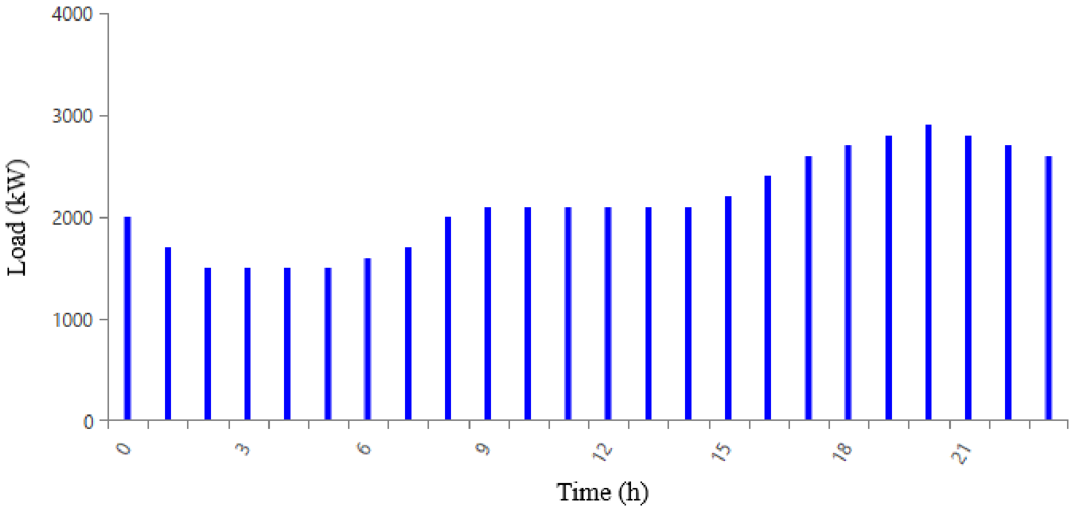


Figure 19. Typical working day profile of the electric load used in mode 1.

Figure 19 illustrates consumption of electricity in normal everyday life. Electricity consumption is expected to be lower at night but will increase in morning as commercial and industrial electricity consumption increase. In afternoon, electricity consumption will increase further as electricity is consumed in leisure time at home.

Daily electric load profile in mode 2 is similar compared to mode 1 but load is smaller because part of energy is generated as thermal energy. Also, in this consumption pattern is used ordinary everyday life. The electric load profile for mode 2 is shown in Figure 20.

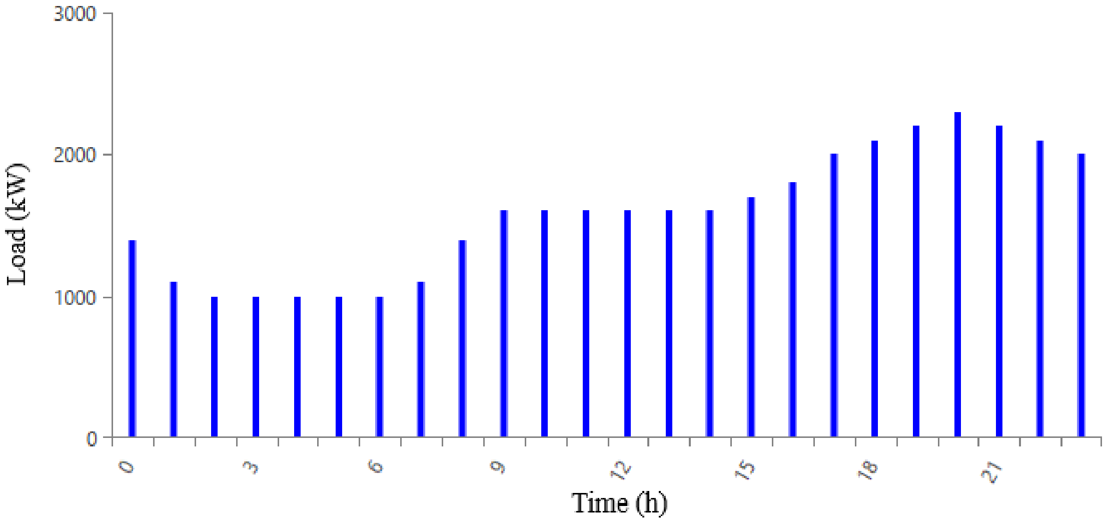


Figure 20. Typical working day profile of the electric load used in mode 2.

Shape of the graph in Figure 20 is similar to that of Figure 19, but the load is smaller because in mode 2, part of energy is produced as thermal energy. Depending on electricity consumed, the shape of the graphs may vary depending on season or day of a week. If electricity is needed for heating, it will be needed more during cool season, which runs from June to September in Kenya, and less during warm season, which is between February and April. Because of low industry in Nairobi, electricity is consumed more for residential use than for industrial use. Based on this, weekends are likely to consume more electricity than weekdays when people are at work. (Expert Africa 2017.)

Consumption of thermal energy is supposed to be somewhat smoother, but consumption at day time is slightly higher compared to night time. Thermal energy may be needed to heat houses, whereby need for thermal energy is higher during the above-mentioned cool season and correspondingly lower during warm season. Daily profile of the thermal energy load in mode 2 is shown in the Figure 21.

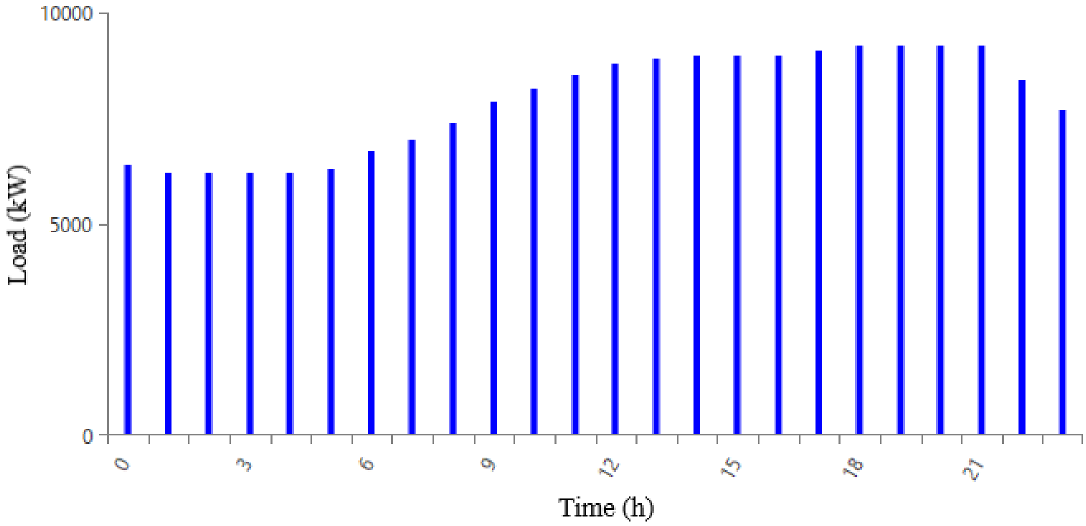


Figure 21. Daily profile of the thermal load used in the simulations in mode 2.

Since power output of the waste incineration power plants is steady, but energy consumption varies according to time, energy has to be stored for a moment. As an electrical energy storage model is used a lithium-ion battery, which is connected to the DC power network. The battery is connected to the power plants through a converter. The CHP generation optimization model includes a thermal load controller as well as a boiler. When enough electricity is supplied to the electric load, the thermal load controller directs the rest of energy to the thermal load. The boiler acts as a compensator for the thermal load, if necessary. Table 11 specifies the costs of the electric storage and converter. The thermal load controller is not included in the optimization, so its parameters need not be defined. The only boiler parameter is efficiency and it is set to be 85 %.

Table 11. Costs for components in the model.

Component	Capital cost ($)	Replacement cost ($)	O&M cost ($/year)
Lithium-ion battery 1 MWh	700 000	560 000	10
Converter 1 000 kW	800	750	10

5.2 Simulations and optimizations in two operational modes

As results of simulations are obtained sensitivity analysis and optimization results. Sensitivity analysis issues simulation results with different sensitivity variables. In this study, nominal discount rate and waste fuel price described as waste fuel price are used as sensitivity variables. Waste fuel price depends on many factors, and in order to simplify a simulation, waste fuel price is basically a constant value of 1, which includes only the price of fuel itself and not a transport.

In simulations, effect of the waste fuel price on the results of the simulations is investigated, whereby the price of fuel serves as a parameter of the simulation. There are three values for this variable when using in addition to a standard price of 1 $/kg, a half price, 0,5 $/kg, and a double price, 2 $/kg. The second variable in simulations is a nominal discount rate, for which values of 3 %, 6 % and 12 % are chosen.

The simulations are divided into two modes according to energy form generated. In mode 1 simulation are considered when energy is generated as electricity only and in mode 2 according to CHP generation. The results of simulations provide both sensitivity cases and optimization results with the selected parameter values.

5.2.1 Mode 1: Distributed waste incineration power plant electricity generation

Mode 1 uses only electricity generation and its simulation results are shown in Table 12.

Table 12. Costs of mode 1 with two parameters: nominal discount rate and waste fuel price.

Simulation run	**Parameters**		**Cost**			
Simulation run	**Nominal discount rate (%)**	**Waste fuel price ($/kg)**	**NPC (M$)**	**Cost of energy ($/kWh)**	**Operating cost (M$/yr)**	**Initial capital costs (M$)**
1	12	0.5	1 210 618	8 508	145 733	375
2	3	0.5	3 750 152	8 506	145 737	375
3	6	0.5	2 297 442	8 507	145 736	375
4	12	1	2 420 742	17 013	291 453	375
5	3	1	7 499 470	17 011	291 456	375
6	6	1	4 594 246	17 012	291 455	375
7	12	2	4 840 990	34 022	582 891	375
8	3	2	14 998 110	34 020	582 894	375
9	6	2	9 187 854	34 021	582 893	375

Table 12 shows the costs of distributed electricity generation with different sensitivity values. In the first column of the costs is net present cost (NPC), which is present value of installation and operating costs of the system components over the lifetime of the project. Therefore, NPC in this study means system life cycle cost. The next column shows the cost of electricity (COE) which is net present value of the unit-cost of electricity over the lifetime of the system. In addition, the costs include the annual operating costs and investment costs for system.

By comparing costs, is noticed that the nominal discount rate is affecting the most on NPC. With the lower nominal discount rate is received the higher NPC. This is also reflected in Figure 22 in Appendix 1, where total life cycle cost is depicted as a surface plot of change in nominal discount rate and waste fuel price. The waste fuel price affects costs associated with regular operations, in other words, the COE and operating cost. As waste fuel price increases, the COE and operating costs rise in a same proportion. Surface plot of the total operating cost with change in nominal discount rate and waste fuel price is shown in Appendix 1, Figure 23. Figure shows that change in nominal discount rate has a little effect on the total operating costs and change in operating costs is caused by change in waste fuel price.

The energy production of each power plant in study case 1 is demonstrated in Table 13. Production volumes are in line with the generation capacities shown in Table 3, as the operating time of all power plants is same.

Table 13. Annual energy production of waste incineration of the six power plants (PP1–PP6) in mode 1.

	PP 1	PP 2	PP 3	PP 4	PP 5	PP 6
Annual production (TWh)	5.42	10.84	3.61	5.42	5.42	3.61

Once the simulation is complete, the program performs optimization by looking for the best option in the simulations. In this study, optimization is performed based on system NPC, in other words life cycle cost. The optimization results for mode 1 are shown in Table 14.

Table 14. Optimization results for mode 1.

Parameters		**Cost**			
Nominal Discount Rate (%)	**Waste Fuel Price ($/kg)**	**NPC (M$)**	**COE ($)**	**Operating cost (M$/yr)**	**Initial capital (M$)**
12	0.5	1 210 618	8 508	145 733	375

The lowest life cycle cost is achieved when fuel price is possible lowest, 0.5 $/kg and nominal discount rate is the maximum possible, 12 %.

5.2.2 Mode 2: Distributed waste incineration power plant CHP generation

Mode 2 uses combined heat and power generation and its simulation results are shown in Table 15.

Table 15. Costs of mode 2 with two parameters: nominal discount rate and waste fuel price.

Simulation run	**Parameters**		**Cost**			
Simulation run	**Nominal discount rate (%)**	**Waste fuel price ($/kg)**	**NPC (M$)**	**Cost of energy ($/kWh)**	**Operating cost (M$/yr)**	**Initial capital costs (M$)**
1	12	0.5	1 210 548	11 485	145 725	375
2	3	0.5	3 749 936	11 483	145 729	375
3	6	0.5	2 297 310	11 483	145 727	375
4	12	1	2 420 603	22 965	291 436	375
5	3	1	7 499 039	22 963	291 439	375
6	6	1	4 593 982	22 964	291 438	375
7	12	2	4 840 711	45 926	582 857	375
8	3	2	14 997 240	45 924	582 861	375
9	6	2	9 187 324	45 924	582 860	375

Table 15 presents the costs of distributed CHP generation with different sensitivity values. In this case, the cost of the system is near same as in case 1 except for the COE. It is higher because part of energy is used for thermal energy generation. The corresponding surface plot of total life cycle cost as in case 1 is shown in Appendix 2, Figure 24 and surface plot of total operating cost is shown in Figure 25.

The difference between simulation modes 1 and 2 is better reflected in production volumes. Table 16 demonstrates energy production of each power plant in mode 2. Compared to these production volumes in production volumes shown in Table 13, it seen that, energy production in case 2 is more than four times higher than in case 1.

Table 16. Annual energy production of waste incineration of the six power plants (PP1–PP6) in mode 2.

	PP 1	PP 2	PP 3	PP 4	PP 5	PP 6
Annual production (TWh)	24.10	48.19	16.06	24.10	24.10	16.06

The results of mode 2 optimization obtained from the simulations are shown in Table 17.

Table 17. Optimization results for mode 2.

Sensitivity		**Cost**			
Nominal Discount Rate (%)	**Waste Fuel Price ($/kg)**	**NPC (M$)**	**COE ($)**	**Operating cost (M$/yr)**	**Initial capital (M$)**
12	0.5	1 210 548	11 485	145 725	375

The results of mode 2 optimization can be deduced from the results of mode 1 optimization because the simulated modes are similar, and same values are used as simulation parameters. The lowest life cycle cost in mode 2 is also achieved with the waste fuel price of 0.5 $/kg and nominal discount rate of 12 %.

6 ANALYSIS AND NEXT STEPS

This chapter analyzes the objectives set for the thesis in the introduction and assesses how well the objectives are achieved. The model created in this thesis also considers improvements to make the simulation model more reasonable.

6.1 Evaluation of the realization in fulfilling the objectives

The object of the study is to investigate the power generation capacity and costs of the waste incineration power plant. The power generation capacity of the modular waste incinerator unit is known, so the capacity of the total waste incineration power plant can be calculated based on these. The cost calculation is based on previous studies of waste incineration power plants. The costs in these studies varied significantly, for example, depending on the size and structure of the waste incineration power plant. The final cost calculation is made based on several scientific studies and evaluating the most realistic costs.

Calculated costs are utilized in modelling by simulating the capital and O&M costs of the pilot waste incineration power plant based on them. The results of the simulations are consistent with theoretical values. Actual costs of the pioneer project are though difficult to estimate accurately before the pilot project is implemented. In addition, costs vary by region and cost of such a project varies between developing countries and, for instance, Finland.

The study is also supposed to be a pilot study that could be used in addition to this project in other similar projects. Implementation of waste incineration power plant project vary compared to each other, but this thesis also provides some guidance for other waste incineration power plant projects. Based on the realized projects the capital and O&M costs can later be specified.

6.2 Expanding the developed model

The simulation model used in the study is simplified to facilitate the implementation of simulation. In the model used only main components for simulation were placed, such as generators, loads and energy storages. With this simplified model essential facts for the thesis can be simulated, such as cost calculation of waste incineration power plants.

In the model were only generators described waste incinerators as power sources. In practice, waste incineration power plants are likely to generate energy alongside other energy sources and the generated electricity is supplied to the grid. However, energy generation of the waste incineration power plants is steady, so its operation does not change significantly from thesis perspective if the incinerators were grid-connected. In addition, design of the used program limited the implementation of the study because program was designed for micropower generation modelling. For this reason, the simulation model has to be adapted to the constrains of the program.

In addition to the model generators, the loads to be used had to be adapted to the power generated by the generators. In a real project site, the load is determined by load in a destination city and an actual power generated by the waste incinerators. The load models used were designed to keep the load at a suitable size for the production of waste incineration power plants and also to follow the typical load model shown in Figure 17.

The waste incineration power plant under investigation may generate steam, electricity or combined electricity and thermal energy. The power plant may also generate these forms of energy in a suitable proportion. In the modelling steam was left out of the simulations and electricity and CHP generation were simulated separately. O&M costs of incineration power plants resulting from simulations will change if various energy forms were produced simultaneously. The cost simulations are indicative, so the results will not change significantly with the output of the power plant. In practice, generating different forms of energy at same time would require a control system which would monitor consumption of those forms of energy and control output of the incineration power plant accordingly.

7 CONCLUSIONS

The consequences of the study resulted in methods that can influence the balance of power generation of the waste incinerator and the cost calculations provided by the *Homer Micropower Optimization Model* based on the cost of the input components. Capital, replacement and O&M costs for components as well as lifetime and other necessary inputs were entered to the program. Based on these, program resulted in total net present costs, capital costs, O&M costs and costs of electricity using two parameters, nominal discount rates and waste fuel prices. Other results provided by program were, for instance, information, documents and data presentation reports with various simulation time and the energy generated by each waste incineration power plant.

Factors affecting the balance between electricity generation and consumption were investigated comprehensively and solutions were found for these in terms of generation, consumption and energy storage. Energy generation solutions focused on other potential energy sources in Nairobi. As regards consumption, demand side management, where you can find a number to the appropriate solutions, such as energy efficiency were investigated. Since energy generation and consumption are never fully balanced, alternative energy storage solutions are explored.

With a nominal discount rate of 12 % and a fuel price of 0.5 $/kg, capital cost was about 375 M$, total net present cost about 1 210 000 M$ and operating cost about 145 700 M$/yr in both electricity generation and CHP generation modes. Cost of electricity differed between the modes and in mode 1 they were about 8 500 $/kWh and in mode 2 about 11 500 $/kWh. The program considers only the generated electricity in cost of electricity and not the total energy generation. In the CHP generation model is produced less electricity than in the electricity generation model, but in the CHP generation model, some of energy is used for thermal energy generation.

According to the generation capacities shown in Section 3.3 in Table 3, electricity generation capacity in the electricity generation model is about 35 % higher than in CHP generation model. However, the output total in capacity of the CHP model is more than four times that of the electricity generation model. If the generated thermal energy can be utilized, it is more profitable to generate combined heat and power.

Directly to the topic related other studies were found a few. There were a few scientific articles dealing with pilot cities of same type of incinerators around the world. The size and cost of power plants varied greatly in these articles and the most of them were related to electricity generation only. However, the articles contained calculations of capital and O&M costs, and by comparing the information received from the articles reasonable results were delightfully obtained.

8 SUMMARY

This thesis studies generation of distributed waste incineration power plants using modelling and simulation costs of the waste incineration power plant are calculated. The objective of the study is to review alternatives to control of power generation of a modular waste incineration power plant and created a cost calculation model that includes the capital and O&M costs of the incinerator unit. The objective is also to investigate balance between energy generation and consumption using other energy sources, demand side management and energy storages. The focus is on developing countries and a proper city of the pilot project is Nairobi, the capital of Kenya. The research results can later be applied to similar projects in developing countries.

In the theoretical part of the research are presented the technology and structure of the waste incineration power plant. The thesis introduces the most commonly used waste incineration technologies, after which the technology used in the project is examined in more detail. Subsequently also the project implementation aspects and requirements for the project implementation are examined.

The empirical part of the thesis investigates methods. This section examines the factors affecting balance between energy generation and consumption. This is utilized other potential energy sources in Nairobi, demand side management (DSM) and different energy storage technologies. In addition, a waste incineration power plant cost calculation model is created using a pilot project in Nairobi and the Homer micropower optimization model.

In final Chapter 6, the results of the simulation and the achievement of the objectives are examined. One of the aims of the thesis was to develop an indicative cost calculation which is compiled based on several scientific articles. Alternatives to expanding the simulation model and their impact on the results of the simulation are also contemplated, as simulation has been implemented in this study by simplifying multiple factors.

As the results of this thesis are received different methods to control production of waste incineration power plant. In addition, as the result is found project cost calculation including capital costs and operating and maintenance costs, using a developed cost model. In addition to the waste incineration power plant is examined the balance between electricity generation and consumption, regarding current energy production in Kenya as well as demand side management and energy storage methods.

The study topic is extensive and focuses on distributed generation planning and cost calculation. These main goals are achieved, and the study provided a good basis for possible further research. Electricity generated by distributed waste incineration power plants increases electricity generation capacity significantly and electricity generated must be able to be transferred to the grid. The distribution capacity of the electricity grid should be checked and possibly a new replacement grid should be planned. This is one area of the project that still needs further research. The design projects for this type of waste incineration power plant are all unique depending on size of the area and number of inhabitants and always require their own research.

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APPENDICE

Appendix 1. Costs variation in the distributed electricity generation model.

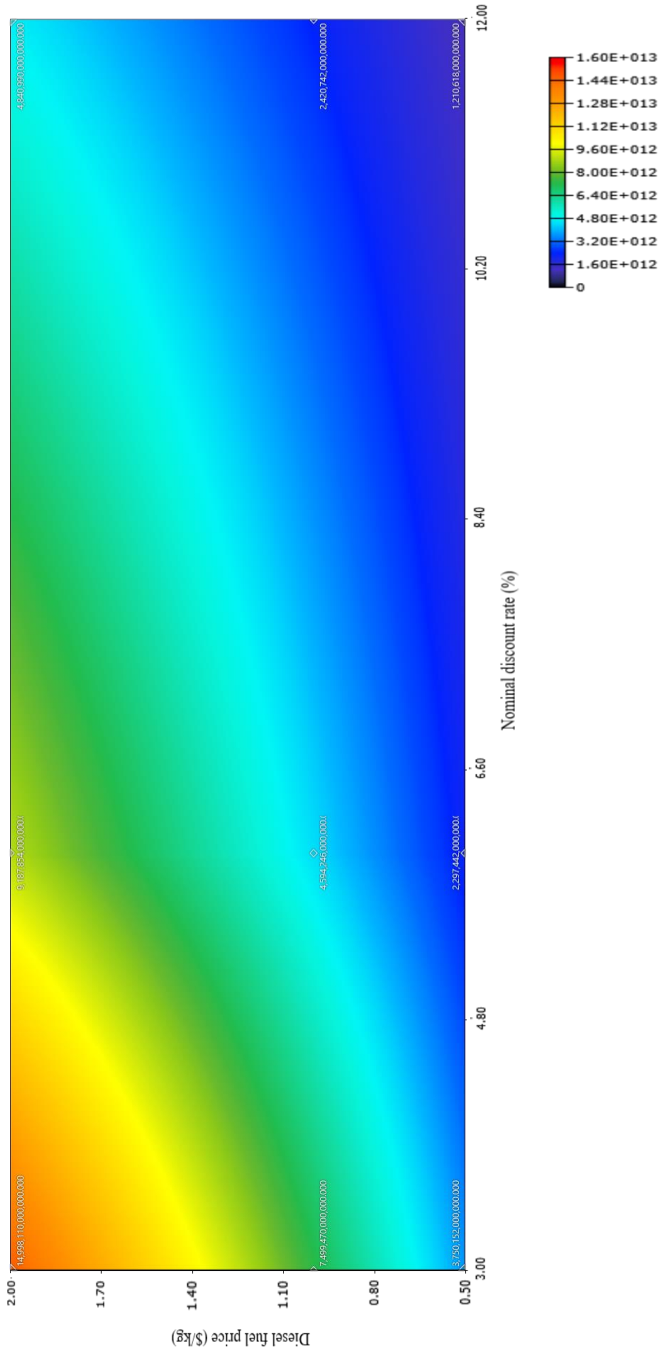

Figure 22. Life cycle cost of distributed electricity generation model.

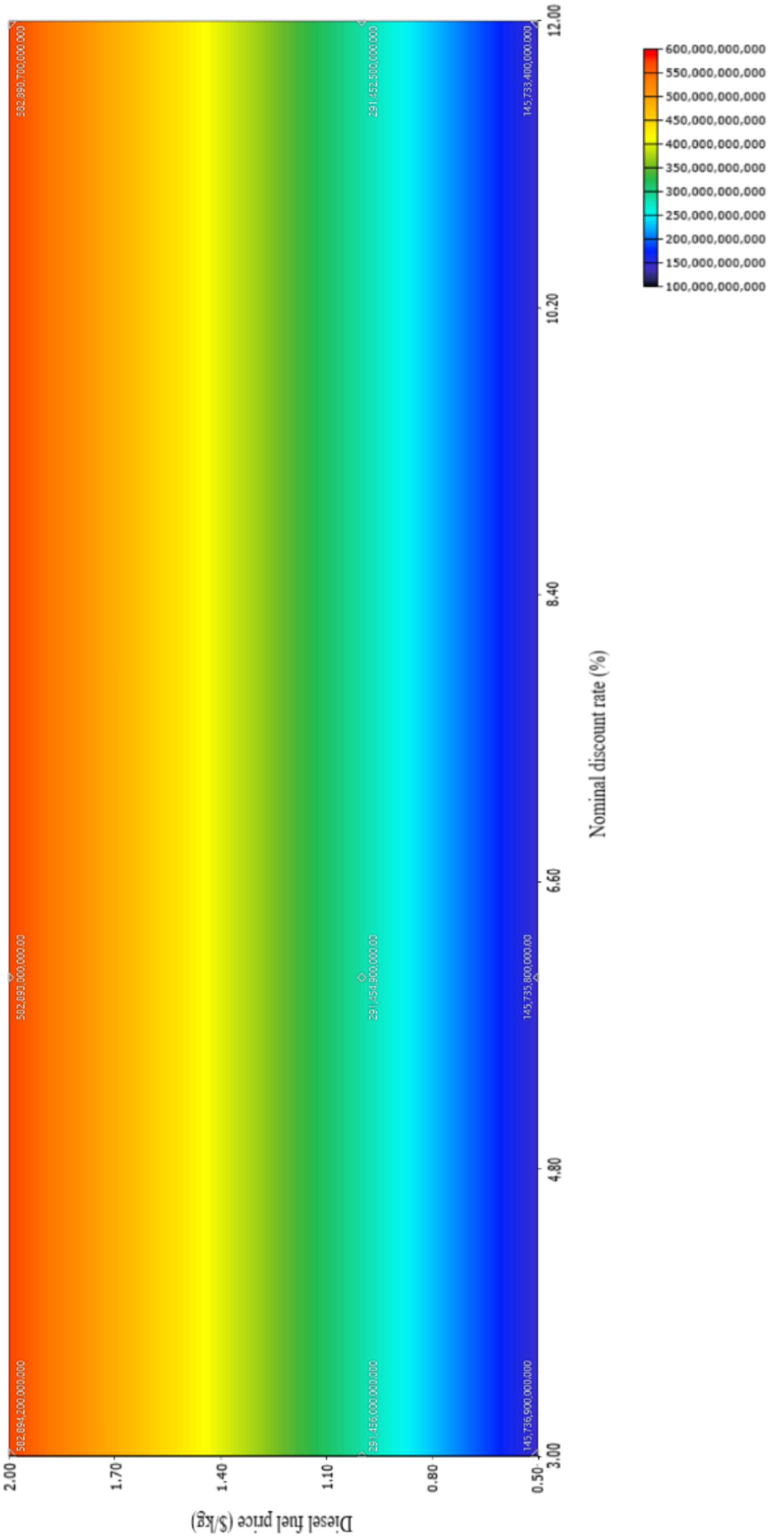

Figure 23. Total operating costs of distributed electricity generation model.

Appendix 2. Costs variation in the distributed model using CHP generation.

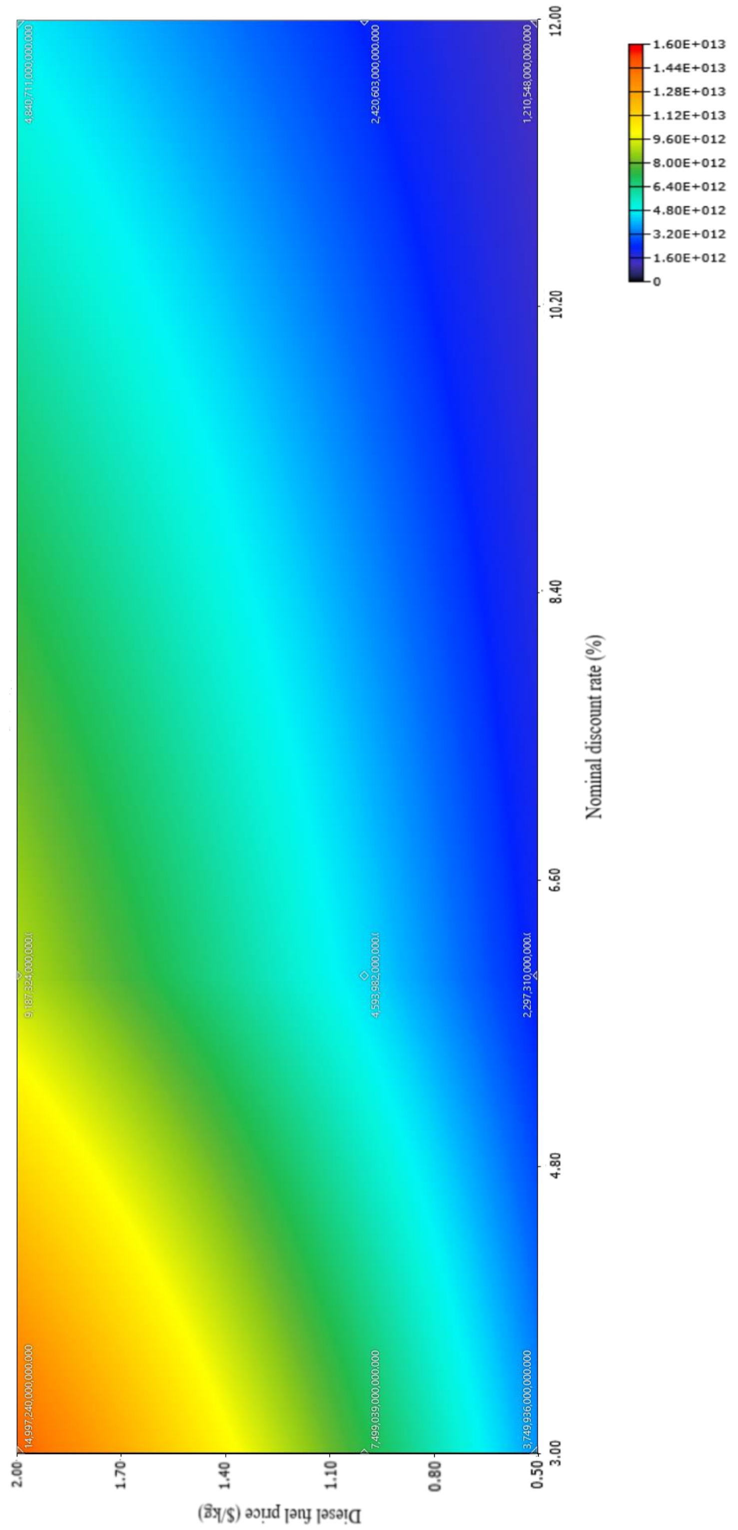

Figure 24. Life cycle cost of distributed CHP generation model.

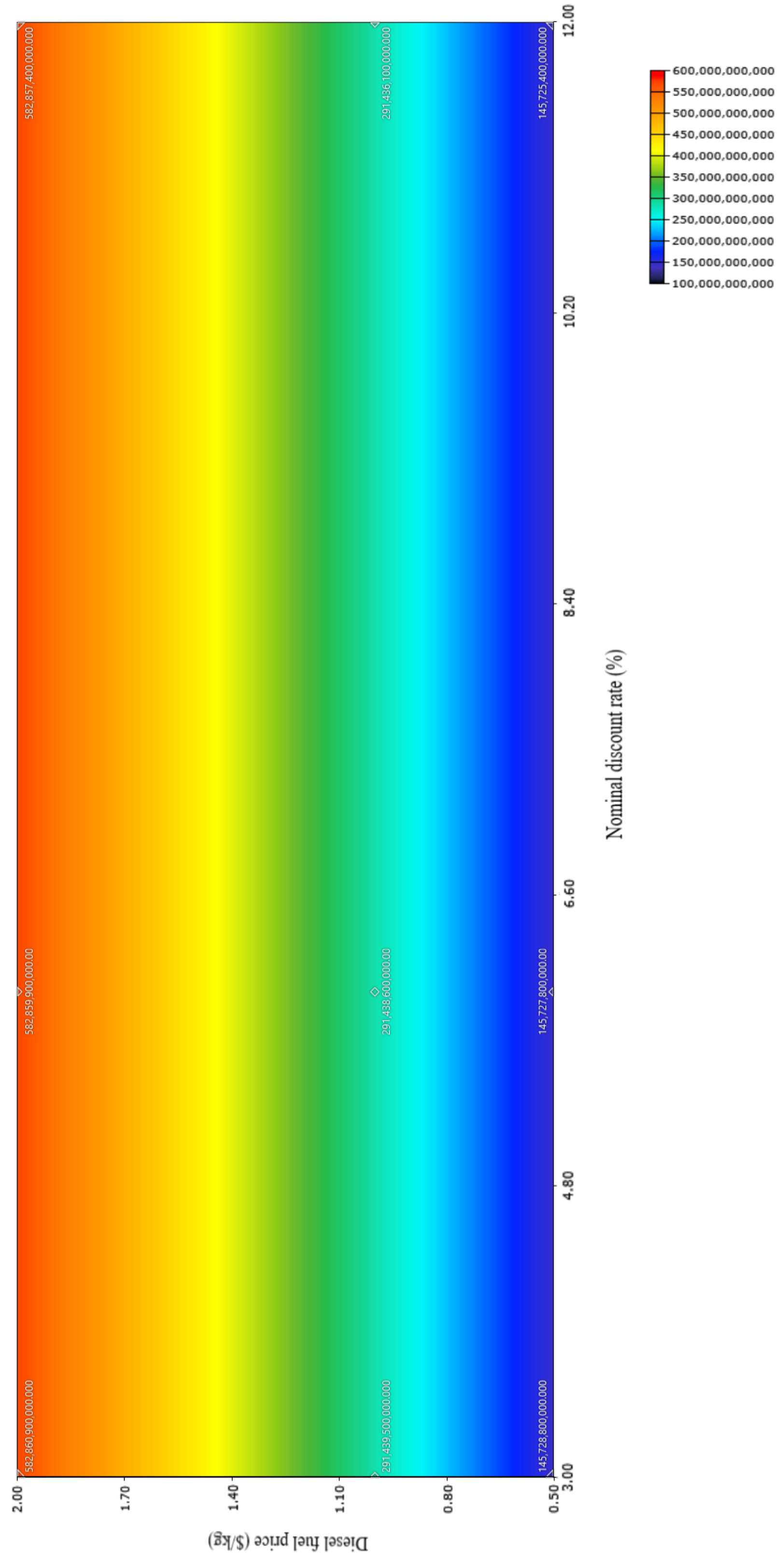

Figure 25. Total operating costs of distributed CHP generation model.