EVALUATING THE HEAT RECOVERY OPTIONS FROM THE GENERATED OILY SLUDGE IN THERMAL POWER PLANTS

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Dissertation submitted in partial fulfillment of the requirements for the degree Master of Engineering

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Abstract:

Oily sludge is a process waste of thermal power plants that use heavy fuel oil for power generation. At present, the oily sludge is sold or incinerated from the power stations belonging to Ceylon Electricity Board. Since the waste heat generated from the incineration process is disposed to the environment without harnessing for effective work, the operation and maintenance cost of incineration is not cost-effective. In this study, the waste heat recovery options were considered based on the sludge treatment methods used in thermal power stations.

The possibility of using the sludge as fuel for micropower generation, hot water generation, and waste heat recovery from the oily sludge incineration was investigated. The study was carried out to determine the potential of recovering the waste heat of the oily sludge incineration process and to investigate the design parameters for a suitable heat recovery steam generator. Furthermore, the calorific value and the constituents in the sludge sample were investigated. As a result of this study, Heat Recovery Steam Generator was found as the most suitable heat recovery method.

The proposed HRSG was modeled, simulated, and optimized using the Engineers Equation Solver (EES) software. From the trial runs, the maximum power output that could be recovered from HRSG is 96.04 kW of energy at a rate of 222.1 kg/h sludge incinerating. Considering the steam mass flow rate for commercially available steam turbines, implementing a micropower generation plant with a capacity of 93.63kW is a feasible project with a payback period of 2.70 years to recover the cost of the investment. Furthermore, the feasibility of the sludge using as a fuel to a sludge fired boiler for power generation and hot water generation were investigated. 107.0 kW of power could be harnessed by burning of sludge at a rate of 204.48 kg/h and 13.36 kg/h of hot water could be generated by burning sludge at a rate of 1kg/h.

Waste heat recovery, Oily Sludge, Micropower generation, HRSG, EES.

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List of abbreviations

CEB	- Ceylon Electricity Board
PHC	- Polycyclic aromatic hydrocarbons
UJPS	- Uthuru Janani Power Station
HFO	- Heavy Fuel Oil
LFO	- Diesel fuel
OEM	- Original Equipment Manufacturer
CPC	- Ceylon Petroleum Corporation
CPSTL	- Ceylon Petroleum Storage Terminals Limited
EES	- Engineering Equation Solver software package
HRSG	- Heat Recovery Steam Generator
ITI	- Industrial Technology Institute
EGT	- Exhaust gas temperature

Subscript

apr	-Approach point
shs	-Superheated steam
gs	-Flue gas
sw	-Saturated water
go	-Gas out
gi	-Gas in
st	-Steam
f	-Fuel
g	-Gas
t	-Temperature
pt	-Pinch point temperature

Nomenclature

Q	-Heat content(J)
V	-Flowrate of the matter(m^3/s)
m_f	-Mass of the required fuel (kg)
Q_g	-Energy absorbed (kJ)
t_{go}	-Flue gas out temperature (^0C)
m_{st}	-Mass flow rate of steam (kg/s)
t_{g1}	-Flue gas in temperature of HRSG (^0C)
t_{pt}	-Pinch point temperature difference (^0C)
t_{g2}	-Economizer exit temperature (^0C)
h_{apr}	-Enthalpy - approach point (kJ/kg)
h_{sw}	-Feed water enthalpy (kJ/kg)
h_{shs}	-Enthalpy – superheated steam (kJ/kg)
h_{ouis}	-Isentropic enthalpy of steam (kJ/kg)
Q_e	-Heat required (kJ)
C_f	-Calorific value of sludge
η_{stm}	-Turbine mechanical efficiency
h_{sw}	-Enthalpy of saturated water (kJ/kg)
t_s	-Saturation temperature of the water
Δt	-Temperature difference in the substance
h_{s2}	-Enthalpy of steam evaporator(kJ/kg)
h_{ou}	-Enthalpy of steam at turbine out (kJ/kg)
Q_{ex}	-Extracted energy percentage
h_{lo}	-Heat loss from the HRSG
P_{stm}	-Steam turbine power output (kW)
η_{Is}	-Turbine - isentropic efficiency
ρ	-Density of flue gas (kg/m^3)
C_{pg}	- Value of specific heat - flue gas
h_{shs}	-Turbine inlet enthalpy (kJ/kg)

η_b	-Efficiency of the boiler
t_{gi}	-Flue gas in temperature (^0C)
$\dot{m}_f$	-Mass flow rate of sludge (kg/h)
m_g	-Mass flow rate of flue gas (kg/s)
m_{gs}	-Mass flow rate of gas (kg/s)
t_{g1}	-Temperature - flue gas in (^0C)
t_{g4}	-HRSG exit temperature (^0C)
t_{g3}	-Evaporator exit temperature (^0C)

1.0 INTRODUCTION

The national grid of Sri Lanka is powered by thermal power, hydropower, wind power, and solar photovoltaic power. A major contribution is from thermal power which is 79 % and the next biggest contribution is from hydropower, which is 16 %. Wind and photovoltaic are still a very small contribution to the national grid. As for the data from Ceylon Electricity Board, the peak electricity demand in Sri Lanka as reported in August 2019 is nearly 2500 MW. Considering the thermal power generation in Sri Lanka, thermal coal is contributing 35% and thermal oil is 44% [1]contributing.

The main fossil fuels which are used for thermal power generation are Naphtha, Diesel, and Heavy Fuel Oil (HFO). HFO is used in Gas turbines as well as Engine-driven thermal power stations. Naphtha is used only in Gas Turbines [2]. Among the above-mentioned fuel, Naphtha and Heavy fuel oil are the cheapest fuels which are used for thermal power generation. And the heavy fuel oil needs to be separated and purified before ejecting to the engines. The main reason for this is,

- to protect the engine from abnormal wear and corrosion by eliminating solid impurities, suspended impurities, and the water
- to prepare the fuel oil for the recommended condition which suit the proper combustion

By heavy fuel oil separation, the oil sludge will be generated. Mostly in the engine-driven power stations, a large quantity of oily sludge will be generated when the engines are in running condition. Since the thermal power stations are running continuously the oily sludge is continuously being generated.

Oil sludge is a complex mixture of oil, water, metal impurities, and solids [3]. Also, oily sludge can be considered as a stable emulsion of aqueous droplets with solid particles dispersed in an oily liquid with high viscosity [4]. Because of the toxins contained in oily sludge such as polycyclic aromatic hydrocarbons (PHC) and heavy metals, it is considered hazardous waste. In Sri Lanka also oily waste is considered hazardous waste under the scheduled waste category [5].

Improper disposal of this oily sludge will create serious problems for the environment such as polluting the water bed and pollution of the soil. The oil sludge contaminated soil will create a deficiency, inhibit seed germination, and cause restricted growth or it demises the plants on contact. Furthermore, due to the high viscosity of the oily sludge, the components in the oily sludge could be settled in soil pores or could be absorbed into the soil mineral constituents. The polycyclic aromatic hydrocarbons in the oily sludge are genotoxic to human and other ecological receptors [6]. And if the oily sludge penetrates down via the soil and mixes with the groundwater, which links with the other aquatic systems can cause serious problems for the aquatic lives.

Considering the hazardousness in the oily sludge, a safe and economical method for the disposal of oily sludge is required. If it is possible to reuse the sludge it would bring economic benefits to the country too. Oily sludge can be used as a core fuel for small furnaces and oil-fired boilers, such as the oil-fired boilers used in textile industries, metal industries, production processes like shoemaking and refectory industries. In Sri Lanka too there is a market value for the generated sludge. In the Colombo suburb, the power stations owned by Ceylon Electricity Board (CEB) are normally selling their sludge to authorized buyers who are having the environmental certificates required for the sludge disposal. However, peripheral industries need to be developed in the Jaffna peninsula to use the sludge generated in the Uthuru Janani Power Station (UJPS). For which the properties and the constituents of the sludge have to be analysed. This would be a case study for 'Waste to Use' opportunities for sludge generated in other thermal power stations around the world too.

Figure 1:Uthuru Janani Power Station (Original in colour)

Figure 2:Installed incinerator at UJPS (Original in colour)

1.1 Background

Heavy Fuel Oil (HFO) and Diesel fuel oil (LFO) are the main fuels used for the engines in thermal power generation. The HFO is received to the fuel storage tanks through a pipeline or transported from the bowsers. Before using HFO it should be separated and cleaned. Mainly the fuel is separated by the fuel separators to obtain the purified HFO which can readily be supplied to the engines. Fuel sludge (HFO Sludge) will be formed in this process as a waste or a byproduct. The quantity of HFO sludge is higher compared to the other sludge generating sources from diesel engines in a thermal power station, typically 1% to 1.5% by volume of HFO is lost as sludge [7]. The other oily sludge generating sources from the typical IC Engines which are used in thermal power generation are as follows [8],

- Sludge generating from, HFO fuel separators
- Sludge generating from, lube oil separators
- Oily residues (sludge) from the engine pits
- Oil and sludge coming from washing bays
- Removed lube oil and other lubricants from the engine and pumps
- Dirty oil lines from the engines

The generated oily sludge from the above-mentioned methods is collected in a separate tank called “the sludge tank”. The HFO sludge from fuel separators and sludge generated from the lube oil separators are directly added to the sludge tank. All the other effluent water contaminated with oil is collected in an oily water settling tank.

The collected oily water is sent through the Oil Skimmers to skim the collected oily water. By the skimming process oil in the water is grabbed by the skimming action and collected in the sludge tank. To evaporate the water contaminants in this oil, the system is heated using steam to keep the unit at 80^0C to 90^0C when in operating condition as well as when in the oily skimmers and the sludge tank. The rejected water from the oil skimmers is guided to the oily water treatment plant where the oily water is further treated. From the treatment plant, oil particles in the water are removed up to 7ppm to 10ppm in wastewater. The captured oil from this treatment process is again pumped into the sludge tank. From the above-mentioned methods, sludge and oily waste are generated and collected in the sludge tank. Through the above-mentioned processes for the last two years, the annual average sludge generation volume at UJPS is 110.8 m^3, which is around metric tons 115.41.

Considering the used lube oil generation, per day 90 liters of used lube oil is drained from a single-engine to maintain the Original Equipment Manufacturers (OEM) recommended Total Base Number (TBN) value in the lube oil from engine sump. The used lube oil is collected in the used lube oil tank of the power station. From all three engines, nearly 270 liters of used lube oil need to be removed to maintain the TBN value in the engine sump on a particular day when the engines are running for 24 hours continuously. In a particular year, if all three engines were run, theoretically 98,550 liters of used lube oil would be generated but, actual values will differ because the engines are not running continuously. Hence the lube oil data were collected monthly basis for a period of April 2018 to July 2019. For this period used lube oil 66,792 liters were generated. Apart from this from the engine routine maintenance, nearly 5000 liters of lube oil is removed from a single-engine. From all three engines, 15,000 liters of lube oil will be generated from running hour-based maintenances works. However, in the above period, no engine maintenance occurred. Hence the total used lube oil generation was 66.792 m^3.

Waste flow diagram – Oily Water and Sludge

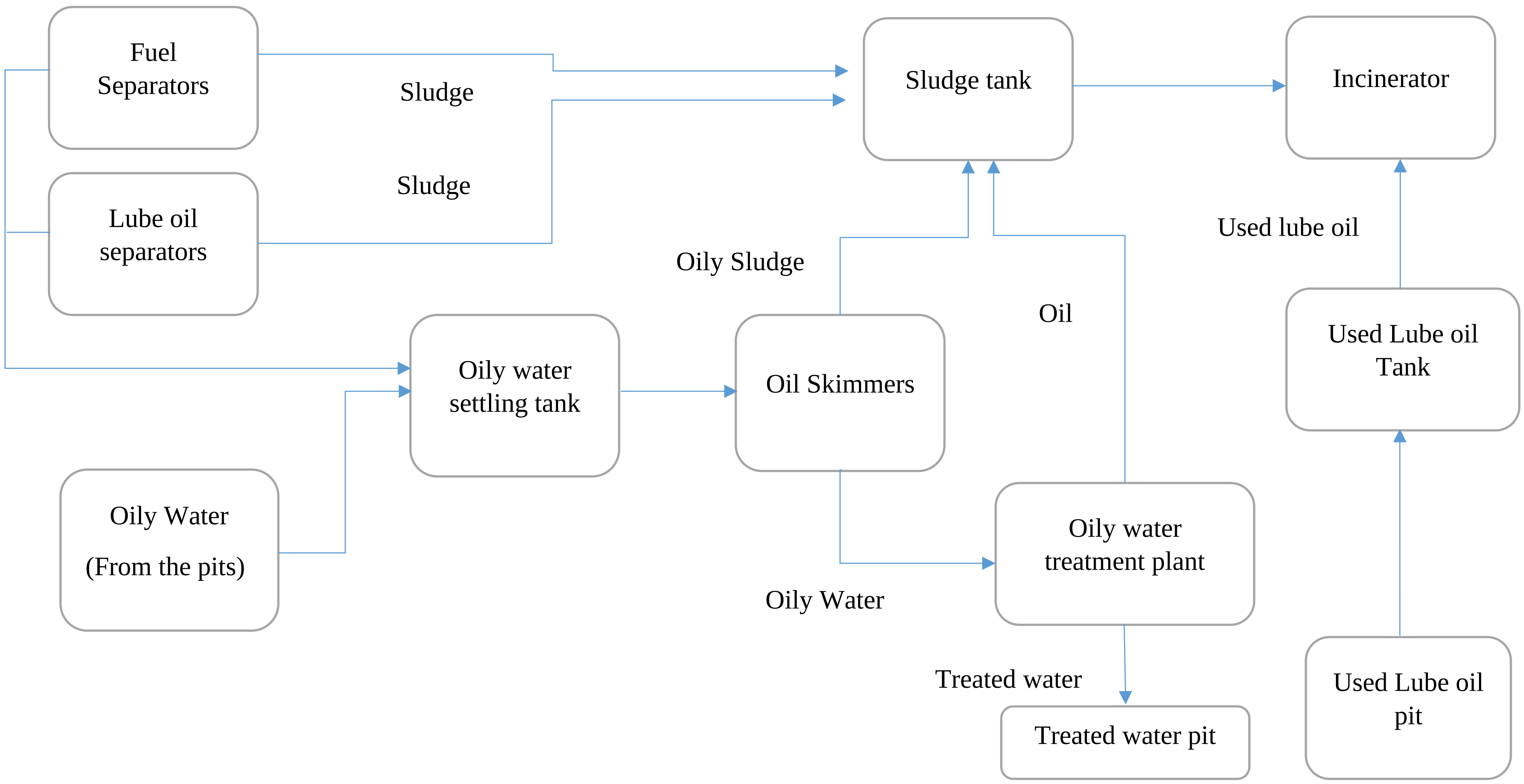

Figure 3:Waste flow diagram (Oily water and sludge)

1.2 Problem Formulation

The problems associated with sludge formation can be categorized into several areas as described in the subsections below.

1.2.1 Sludge storage

The usable capacity of the sludge tank is 5 m^3 and comparatively this tank is small. Though the sludge tank was designed for this capacity, in the present situation, the capacity is not enough to store the sludge because of the running pattern of the power station. Therefore, the generated sludge needs to be removed continuously to maintain the safe level of the tank to retain the availability of the plant.

1.2.2 Selling sludge waste

Since Uthuru Janani power station was located in the northern part of the country it was a very difficult task to find a buyer to sell the generate sludge and the used lube oil. The main reason for the unavailability of buyers in the Jaffna Peninsula was the unavailability of industries and the unavailability of certified waste disposal parties. Also, the buyers from Colombo are not much interested in buying sludge because of the distance to Uthuru Janani Power Station from Colombo, considering the transport cost.

According to the UJPS past data in the year 2015, a quantity of used lube oil has been sold. Other than that, even after the tender is published still no buyer is quoting for the bid. Due to the present environmental rules and regulations, purchase this type of waste is restricted and only the buyers who have the waste disposal license from the Central Environment Authority are allowed to buy. Although all the other Colombo suburb power stations are selling the generated sludge and earning money from the generated waste sludge, here at Uthuru Janani Power Station, selling of sludge is impossible.

1.2.3 Incineration of sludge

The generated sludge and the removed lube oil are presently being incinerated at UJPS due to the unavailability of the buyers to sell the sludge. To eliminate the oily sludge and the used lube oil, currently a minimum cost of Rs. 55,000.00 occurrs. Since the generated sludge is incinerating without any problem, there should be an opportunity to further use the sludge economically and extract the energy from the waste to harness the energy for a positive work from it.

Furthermore, a survey conducted with a buyer who was quoted for the sludge at Sapugaskanda Power Station noted that currently, a textile industry at Aweissawela-Board of Investment (BOI) and metal industries are purchasing the sludge from this buyer for their energy requirements.

1.3 Aim

To evaluate the feasibility of the heat recovery options for heavy fuel oil-based Thermal Power Plants

1.4 Objectives

Objectives are organized as follows to achieve this aim

- To understand the state of the art of different uses of sludge waste
- Evaluating thermophysical properties of the oily sludge from the heavy fuel oil-based power station to investigate different methods for heat recovery from oily sludge
- Propose a suitable model for the heat recovery process

1.5 Methodology

The following methodology was used to achieve the above objectives of the research.

- Phase I:
  - Literature review on waste sludge of thermal power plants and usage
- Phase II:
  - Data collection - on relevant sludge data form oil-based thermal power station in the country
  - Laboratory tests on sludge calorific value and its constituents
- Phase III:
  - Data analysis and simulating for different heat recovery option

    Selecting the most suitable heat recovery option considering technical and economic factors

Methodology - Flow Chart

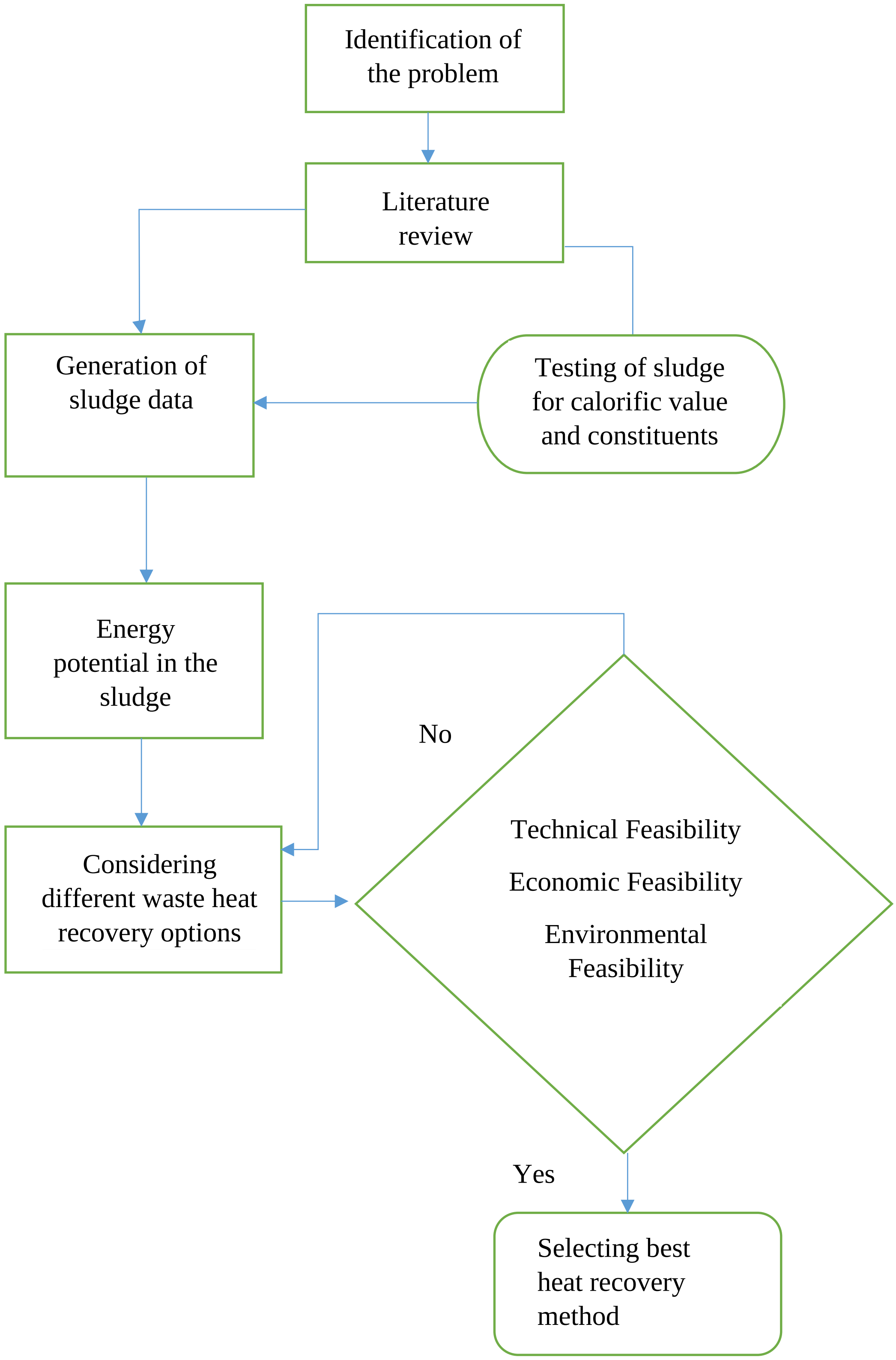

Figure 4: Flow chart of the Methodology

2.0 LITERATURE REVIEW

Waste needs to be classified to understand the risk of the waste to the environment and for all living beings. By understanding the criticality of the generated waste, it will be effectively complying to eliminate the dangerous wastes or either finding out suitable methods or techniques to reuse the generated waste wisely rather eliminating them.

2.1 Classification of waste

With the development of humans, energy plays a vital role in human needs. However, when generating energy wastes are also generated. Among the generated wastes, some of the waste is recognized as hazardous to the environment. To protect nature from waste, various rules and regulations are implemented. Considering the energy generation via heavy fuel oil burning and generating electricity oily wastes and sludge is being generated. To eliminate the generated waste, economical methods should be developed for using the generated oily wastes and sludges economically.

Human activities are always generating waste in the form of solid, gas, or liquid. With urbanization and the growth of large conurbations, waste has become a serious problem [9]. Globalization, rapid population growth and industrial development have led to the generation of a huge quantity of industrial waste during the last few decades [10].

According to the Environmental Act of Sri Lanka, waste can be defined as a substance that could be solid, liquid, gas, or radioactive, dumped or emitted to the atmosphere, thus causing changes to the environment destructively [11]. Waste classification is the process by which waste is assigned to one or more classes based on its properties, characteristics, components, or other properties [12]. The following factors are considered in the design and implementation of waste classification methods: being systematic and hierarchical, practical maneuverability, and expansibility. Waste can be divided into two groups based on waste generating sources as municipal solid waste and industrial waste.

According to hazardous characteristics, waste can be divided into hazardous waste and non-hazardous waste [13]. Considering the above factors waste can be categorized into the following types.

Table 1- Waste category with the waste type

Waste Category	**Waste Type**
Municipal waste including household waste	Non-hazardous
Biomedical waste including the clinical waste	Hazardous
Industrial waste	Hazardous
Radioactive waste, explosive waste, and electronic	Hazardous

Source: Sri Lanka Central environmental authority [11]

2.1.1 Hazardous wastes

Waste is characterized as hazardous if it possesses any one of the following four characteristics: Ignitability, corrosiveness, reactivity, or toxicity [13]. Hazardous wastes, which are usually the waste by-products of industrial processes, present immediate or long-term risks to humans, animals, plants, or the environment

- Ignitability of waste can be simply understood as, whether the waste can catch fire under certain conditions. For example, liquids with a low flash point, substances that cause a fire when it absorbs the moisture or friction sensitive and compressed gasses which are ignitable.
- Corrosiveness of waste can be simply understood by the acidity or alkalinity of the waste and whether capable of corroding metal. If acidic the ph values will be less than or equal to 2 or if alkalinity is greater than or equal to 12.5.
- Reactivity of waste can be simply understood as the instability of the waste under normal conditions which leads to explosions, create toxic gases when mixing with water, and violent reaction when mixed with water.
- The toxicity of waste can be simply understood as waste that will be harmful or fatal when absorbed. These types of waste will be more poisonous to groundwater which will lead to long term health issues or will lead to carcinogenic, mutagenic, and teratogenic effects on living beings [14].

In the viewpoint of Paul N. Cheremisinoff, industrial hazardous waste can be categorized as all non-product or product hazardous outputs from industrial processes to the environment even if the waste is within the permitted limits [15]. Some researchers define industrial hazardous waste as an unwanted thing produce out of industrial activity as a byproduct or discarded material that has a potential of damaging the environment and /or living being [16].

2.1.2 Sources of hazardous wastes

Hazardous waste is a growing problem in Sri Lanka and various factors contribute to aggravate the issues such as industrial hazardous waste, clinical waste, and electronic waste [17]. Furthermore, the major waste of organic hazardous category stated in Sri Lanka are as follows [18] but no data is available for the quantity of generated waste per year.

- Oil waste (liquid) and semi-solid
- Solvent waste (non-halogenated and halogenated)
- Waste paints, lacquers, varnishes
- Waste agrochemicals
- Wood preservative waste
- Bitumen associated wastes
- Solid waste contaminated with organic materials

Researches have stated that the industries which are mentioned below are the main industries that produce hazardous waste creators in Sri Lanka [18],

- Chemical
- Energy Sector
- Metal sector
- Mineral products
- Textile
- Industrial utility waste
- Timber wood & coir
- Commercial, industrial & residential waste
- Water treatment facilities
- Petrochemical sector
- Pulp and paper
- Rubber

Sri Lankan industries which are having high electricity consumption (than 1 MW) also known as heavy industries; such as iron scrap melting, thermal power generation and manufacture of asbestos cement sheets, etc. [19]. Hazardous waste generated by these heavy industries is bringing harm to human health.

As for the energy requirements for the heavy industries in the Sri Lankan context, the Ceylon Electricity Board is the main power producer in Sri Lanka. For example, the peak demand for the CEB power system was approximately 2499.27 MW on August 06, 2019.

Table 2:Resources vs the generated energy

Resource	**Generated Energy (GWh)**
Thermal Coal	16.04
Hydro	7.46
Wind	2.11
Thermal Oil	19.82

Source: Ceylon Electricity Board Generation data on August 06, 2019

From the above chart, it is clearly shown that the CEB is highly dependent on thermal oil to generate the required electricity. In thermal power generation in Sri Lanka, mainly Coal-fired power station, Gas turbines, Combined Cycle Power Station, and IC Engines are used to generate electricity.

Researches who have analysed the waste generated from power generation stated that the amount of environmental discharges generated in the thermal power plants depends on several factors [20]. There are,

- Fuel type
- Process modifications
- The power production capacity of a plant.

When comparing the waste generation potentials, oil falls between coal and gas while burning coal results in the highest amount of waste production [21]. Furthermore, waste generated at the final stage of each process within each and all systems in power plants is called “process wastes”. Oily sludge generation is the main process waste generated by the thermal power stations.

2.1.3 Oily sludge

Oily sludge is listed as a hazardous waste in Resource Conservation and Recovery Act by Environment Protection Agency America [22]. In Sri Lanka, Hazardous Waste has been defined as Scheduled Waste because oily sludge is a major source of contamination for soil, air, and groundwater especially due to its large yield, treatment difficulties, and potential hazards to the environment [23]. As for the previous researches, the oily sludge can generally be considered as a stable emulsion of aqueous droplets with solid particles dispersed in an oily liquid with high viscosity and also oily sludge varies in content concerning its production source [24].

The oily sludge mainly contains hydrocarbons, water, fractions, soil, suspended materials furthermore the composition of this oily sludge can be expressed by three indicators. They are water content, oil content, and solid content [25]. If this oily sludge is not treated effectively, it will damage the ecological system and cause serious environmental pollution and even harm human health.

(I) Elemental composition

Oily sludge is a very complex mixture having oil in water, water in oil emulsion, and suspended solids. Toxic substances are also included in the oily sludge [26]. Oily sludge is a hazardous waste and the elemental composition of the sludge is Phosphorous, Potassium, Iron, Copper, Calcium, Magnesium, Cadmium, Phosphate, Chromium, Zinc, Sodium, and Lead [27]. Furthermore, the economic impact of the sludge is that the removal and disposal process of the sludge is considerably expensive.

(II) Disposal methods

The disposal methods which are available for the oily sludge are Incineration, Centrifugation of the oily sludge, Microwave irradiation this method is having high energy consumption, high maintenance and operating cost, Electrokinetic method and Ultrasonic irradiation are fast and efficient methods, yet they are still in the laboratory level. Incineration has been an alternative for the disposal of oily sludge with its unique characteristics to minimize the volume and recover energy [28]. Experimental investigations were carried by the researchers to recover the waste heat by oily sludge incineration using the fluidized bed technology. The incineration technology is not only successful in removing the toxicity but also provides a reduction in the volume of waste to be disposed of in addition to waste heat recovery.

(III) Constituents

Oily water contains more than 40% petroleum hydrocarbons in it [29]. Therefore, oil reclamation or removing water and solids impurities removal to recover valuable resources would provide economic and environmental benefits. And the oily sludge is an extremely complicated mixture of saturated and aromatic hydrocarbons, non-hydrocarbons, asphaltenes, resins, silicates, and other impurities formation such as iron, chlorine, and sulfur. No effective method to identify specific components of the oil phase is available even with modern analytical methods such as Gas Chromatography, Nuclear Magnetic Resonance, and the Spectrophotometric method. To reduce interactions among the solid-oil-water phase for recovering hydrocarbons from oily sludge various methods have been developed. There are Solvent extraction, Catalytic Cracking and mechanical centrifugation are the most widely employed commercial approaches and the biological method was Microbial Remediation.

The remaining metals in the sludge, usually in the form of relatively thermally stable, oil-soluble organometallic complexes such as metal porphyrins and derivatives. Conservative methods are available to extract the metal contaminants which are in the oily sludge. They are centrifugation, solvent extraction, and employing chemical and chelating agents contacted with the material. The centrifugal method is effective in water-soluble metal salts [30]. As for the previous research, the analysis of oily sludge the heating value of dry basis and low heating values of wet basis were about 10,681 and 5870 kcal/kg respectively. Since the content of the high values of combustible substance, the waste of oil sludge would be a valuable resource. The ultimate analysis of dry sludge and the contractions of different metal elements in the wet basis of oil sludge are as follows.

Table 3:The ultimate analysis of the dry basis of oil sludge [24]

Component	Weight percentage (wt %)
C	83.94
H	12.01
N	0.81
O	0.96
S	2.06
Cl	0.22

(IV) Methods of metal extraction

Disposal of the sludge which includes heavy metals is a challenging task because metals are non-biodegradable and tend to bioaccumulate. Metal retention in the sludge is influenced by several external factors such as ph., temperature, redox potential, organic matter decomposition, leaching, ion exchange processes, and microbial activity. The mobility of the metals in the sludge was as follows, Ni, Fe, Zn, Cr, and Pb. Most of the metals dissolved in the sludge found to be associated with silicate as exchangeable or bound Fe - Mn oxides except Cr and Cu, which were mainly present on the silicate fraction [31].

Emulsion liquid membrane technique was used to recover the V (vanadium) from the oil sludge [32]. Recovery of vanadium from oil sludge process involves contact of fly ash of the sludge with a sulfuric acid solution followed by purification and enrichment with emulsion liquid membrane process. Fly ash is collected from the sludge burning. Leaching and solvent extraction process are also widely used for to recovery of vanadium from the burned oil fly ash. As for the previous researched data vanadium leaching extraction efficiency, 65% to concentrated sulfuric acid (96% v/v) and recovery efficiency of vanadium from this leaching solution is more than 86 % by emulsion liquid membrane technique. Furthermore, by emulsion liquid membrane technique can be applied to produce pure vanadium from the fly ash leaching solution successfully.

2.2 Uses of waste

Several types of research have been conducted to study the importance of reusing oily sludge. Because it is beneficial to reuse and recover the oily sludge for economic works rather than incinerating to eliminate the waste without reusing [33]. It has been proven that the waste heat from the incineration of the oily sludge could be recovered [34]. Furthermore, oily sludge can be used as a fuel, co-fuel, roadbed material, and for the production process of clay bricks effectively.

2.2.1 As a fuel and co – fuel

Oily sludge could be used as a fuel by adding a treating agent which includes gel breaker, bulking agent, adsorbent, and catalyst. The table number 4 below represents the necessity of the mentioned items which are used for the process of creating oily sludge to solid fuel. It has been investigated that the calorific value of the created solid fuel is 3900 kcal/kg [35].

Table 4 – Function of the treating agents used for the oily sludge

Adding agent	**Reason**
Gel breaker	This will weaken the constancy of the oily sludge and it will change the hydrated water molecules in the sludge to free water from the oily sludge. Which helps to dry the sludge easily.
Bulking agent	This results from the oily sludge quickly dry and easier to be burned.
Adsorbent	This will help to absorb the heavy metals in the oily sludge by preventing creating combustion residue.
Catalyst	This will accelerate the reaction and help to increase the calorific value.

The calorific value of the solid fuel converted from the oily sludge is less than the calorific value of the oily sludge as for the research conducted by Abbas, S [30].

Research has been conducted to study the feasibility of using oily sludge as a co-fuel. The use of oil sludge as an alternative fuel during clinker production was evaluated by the researchers and it was noted that 14% oil sludge could be added to the raw mixture and it was investigated that no variation will occur due to the addition of oil sludge.

Furthermore, it was noted that a noticeable effect did not occur at the combustion of the mixture or in the cement quality. The cement samples satisfied the P.O 42.5 standard. It was also determined that 90.98% of coal could be replaced by oil sludge [36]. Hence the money spent to purchase coal could be saved

Since the oily sludge is having considerable calorific value, it could be used for waste heat recovery and hence electricity could be generated [37] and could be used in the power stations as a waste heat recovery option.

2.2.2 Roadbed material

Researches have investigated that, there is a possibility of using the oily sludge as a roadbed material utilizing Phosphogypsum-based cementitious material [38]. After the solidification process with the Phosphogypsum-based cementitious materials, results were obtained as the oily sludge had excellent road performance with sufficient strength. Hence, investigation of oily sludge can be used as a roadbed material to solidify the body.

2.2.3 Production of clay bricks

A research was conducted to study the feasibility of using the generated oily sludge as a combustible additive for the brick making process. Based on the research data, it was investigated that the optimum mass ratio of clay to oily sludge is 1: (0.09-0.35) the water content in the oily sludge to be 27% by weight.

Furthermore, by weight 22% of oily sludge is using for the production process may reduce a reasonable amount of waste generated and use of the oily sludge for the production of bricks may save the consumption of the clay as raw material and decreases the firing temperature of the bricks [39]. From both the raw material as well as energy was saved.

2.2.4 Waste heat recovery

Oily waste can be completely disposed of by incineration with the excess air and auxiliary fuel. This method is widely used to eliminate the generated oily sludge. Oily sludge incineration can generate a valuable source of energy by recovering waste heat from the incineration process.

2.3 Waste heat recovery technologies

Heat recovery methods are consisting of exchanging the heat between the liquids and gasses and /or liquid transferring the absorbed heat to,

- Preheat the load entering the furnace or boiler
- Power generation
- Used for heating or cooling

The waste heat is the heat rejected by a machine during its operation causing the process to be inefficient. Therefore, it is necessary to incorporate waste heat recovery processes. Methods of waste heat recovery consist of absorbing and shifting the waste heat to a gas or liquid and use it as an extra energy source or for any other [40].

Kilns, Glass furnaces, and Incinerators release hot exhaust gasses to the environment. Using firm well-established systems, the waste heat from those processes can be harnessed to generate electricity [41].

At any temperature, waste heat can be rejected. But the temperature of the waste heat flow is higher, the waste heat recovery process will be easier and could be optimized because the quality of waste heat is high. Hence, it is an important factor to analyze the maximum feasible quantity of recoverable waste heat potential from a source to ensure the success of extracting the waste energy from the source [42].

Waste heat streams are categorized into three temperature ranges as follows [43],

- Low temperature range ($< 230\ ^0$C)
- Middle temperature range ($230\ ^0\text{C} \leq T < 650\ ^0$C)
- High-temperature range ($\geq 650\ ^0$C)

The waste heat of higher grade – economical and successful the application.

To study the possibility of waste heat recovery, it is necessary to illustrate the heat source and surroundings that the waste heat to be transferred. The significant factors which must be considered are as follows.

- Heat quantity
- Heat temperature/quality

- Composition,
- Minimum allowed temperature
- Operating schedules, available

The quality and quantity of waste heat are important. The quantity of the available waste heat can be calculated as follows,

$$Q = v.\rho.c_p.\Delta t \qquad \text{Equation -1}$$

Where,

Q	- Heat content(J) (waste heat available for recovery)
v	- Flowrate of the matter(m^3/s)
ρ	- Density of flue gas (kg/m^3)
Δt	- Temperature difference in the substance.
c_p	- Specific heat of the matter or the substance

If the waste heat potential is high, waste heat recovery application is successful and economical. This could be simply defined as the quality of the waste heat

Different types of technologies are available to capture, recover, and transfer the waste heat from a process and extract it back to the system as an additional energy source. This additional energy source can be used to generate mechanical power and electrical power. Most of the heat recovery technologies which are available for harness the waste heat are energy recovery, heat exchangers employing a waste heat recovery unit [44]. These units are included with waste heat recovery systems such as Recuperators, Heat wheel, Heat pipe, Run around coil, Plate/Shell and tube heat exchangers, and waste heat boilers.

2.3.1 Recuperators

This heat exchanger was used to extract the waste heat from the exhaust gases in industrial processes. Where the two heat transferring fluids are flowing opposite to each other. The heat transfer method of this unit was based on radiation, convection, or combination of both. This method is suitable for air-to-air heat exchanging applications. It is widely applied in the air preheating applications. Hence this unit cannot be used for the heat recovery from oily sludge incineration.

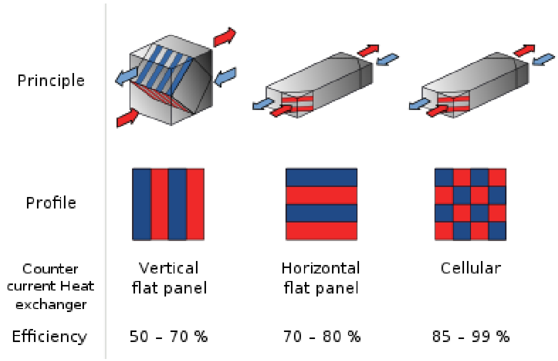

Figure 5:Types of recuperators [45]

2.3.2 Regenerators

In this type of heat exchanger, the heat generated from the hot fluid is intermittently kept in a thermal storage medium before it is shifted to the cold fluid. To achieve this phenomenon the hot fluid is contacted with the heat storage medium, then the fluid is changed with the cold fluid to absorb the heat. This type of heat recovery technology is used in applications such as glass furnaces [46]. Applied in the furnaces to heat the incoming air which coming for the combustion in the furnace. Hence, this unit cannot be used to apply for heat recovery from the oily sludge incineration.

2.3.3 Heat wheel

This type is a rotary type heat exchanger. It is mostly used in applications in low to medium temperature waste heat recovery systems like heating and ventilation systems. Hence this unit cannot be used to apply for heat recovery from the oily sludge incineration.

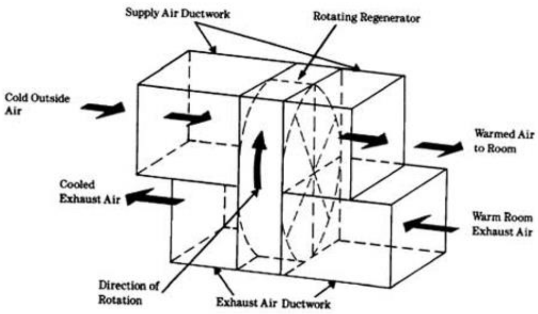

Figure 6: Heat wheel [47]

2.3.4 Heat pipe

The heat transfer principle which was used in this unit was thermal conductivity and phase transition. This unit can be employed to transfer heat from a hot source to a cold source. The fluid employed inside the heat pipe was dependent on the working temperature ranges of the hot and cold reservoir. This unit was mostly used in the temperature range of 200-500k. Water was the widely used fluid within this temperature range. It is because the water is having good thermophysical properties, water is safe to handle, and cheap [48]. This unit was widely used to extract the heat from the combustion gasses and heat incoming air in the furnace system [49]. Hence, this type of heat recovery unit cannot be used for heat recovery from oily sludge incineration.

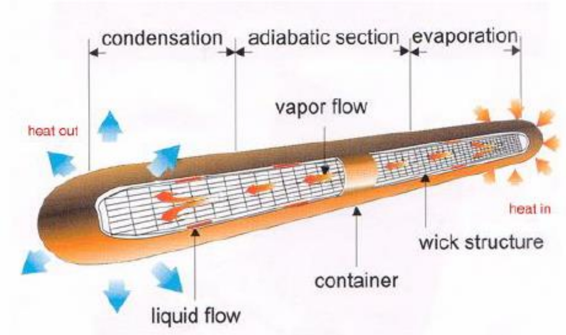

Figure 7 - Heat Pipe [50]

2.3.5 Run-around coil

The heat transferring principle is a bit similar to the heat pipe. In this system, the heat transfer is conducted by employing a heat transfer fluid. In this system, this intermediate fluid is absorbing heat from the hot fluid and transferring it to the colder fluid and the system is a closed-loop system. The intermediate fluid is transferred by a circulation pump. This system is using low-temperature heat recovery systems [51]. Heat recovery from the oily sludge falls in the high-temperature heat recovery application, hence this type of heat recovery unit cannot be used for heat recovery from oily sludge incineration.

2.3.6 Plate heat exchanger

This type of heat exchanger is used metal plates to transfer the heat between the two fluids. The major advantage of this type of heat exchanger was increasing the surface areas by installing metal plates. Hence the fluids are exposed to much larger surface areas [52]. Since this type of heat exchangers are used for heat exchange for two fluids, this type of heat recovery unit cannot be used for heat recovery from oily sludge incineration.

2.3.7 Shell and tube heat exchangers

These two types of heat exchangers represent the types of heat exchanger designs. These heat exchangers are equipped with a bundle of tubes within a steel shell. These heat exchangers can be used for heat transfer applications for two fluids. One fluid flow through the tubes and the other fluid flow over outside of the tubes. Fluid flow within the heat exchanger can be cross and counterflow arrangement. The fluid which is having high pressure is flowing through the tubes while low-pressure fluid flow through the shell [53]. Since this type of heat exchangers are used for heat exchange for two fluids, this type of heat recovery unit cannot be used for heat recovery from oily sludge incineration.

2.3.8 Waste heat boiler

In this type of boilers, exhaust gases are passed over the installed water tubes in the boiler. This waste heat boiler is used in medium to high-temperature exhaust applications. Steam is generated as output. The generated steam can be used for power generation or energy recovery. Pressure and Steam production may depend on the waste heat potential of the exhaust gas application [54]. This type of heat recovery unit can be used to recover the waste heat from oily sludge incineration.

Considered the thermal balance for the boiler, to find out the use full heat required for heating the water in the boiler, the below-mentioned equations can be used.

Applying basic thermal balance, use full heat required for heating the water Q_e,

$$Q_e = \eta_b \cdot m_f \cdot C_v \quad [55] \qquad \text{Equation - 2}$$

Where,

Q_e - Use full heat required for heating the water

η_b - Efficiency (boiler)

C_v - Calorific value of the fuel used to fire the boiler

m_f - Mass of the required fuel

The energy given by the fuel Q_f,

$$Q_f = mf \cdot C_v \quad [56]. \qquad \text{Equation - 3}$$

Where,

Q_f - energy given by the fuel

m_f - mass flow rate of Fuel (or sludge)

C_v - The calorific value of the fuel or (sludge)

To find the energy potential in the flue gas, it is required to find the energy absorbed by the flue gas Q_g. The ratio of the use full heat required for heating the water to Energy absorbed from the flue gas will result in the extracted energy percentage.

The energy absorbed by the flue gas Q_g,

$$Q_g = m_g \cdot C_{pg} \cdot (t_{go} - t_{gi}) \qquad \text{Equation - 4}$$

Where,

Q_g - Energy absorbed from the flue gas

m_g - Mass flow rate of flue gas

C_{pg} - Value of specific heat - flue gas

t_{go} = Flue gas out temperature

t_{gi} = Temperature - flue gas in

$$Q_{ex} = Q_g/Q_f \qquad \text{Equation - 5}$$

Where,

Extracted energy percentage = Q_{ex}

2.4 Waste heat recovery from oily sludge

Waste heat is an energy source, which is generated by a process (fuel combustion and incineration.) Or a chemical reaction, and then released into the environment without reuse for suitable economic purposes. There is considerable opportunity to use the waste heat using heat exchangers and other forms of heat recovery equipment to permit the waste heat to be recovered. There will be considerable savings for the temperature range from 200 ^{0}C to 500 ^{0}C [57]. There are several types of arrangements of heat exchangers, for the optimum heat recovery and operation, a suitable heat exchanger must be selected [58]. By recovering the energy in the flue gas of oily sludge incineration, it can be used to drive a steam turbine and as a heat source [59].

If the oily sludge contains high moisture, it is necessary to pre-treat the oily sludge to remove the moisture to improve the fuel efficiency by removing the water content. This could be achieved by heating the sludge before injecting it into the burner of the incinerator [60].

Several factors govern the waste heat recovery from the incinerator whether it is feasible. Some of them are as follows [61],

- The particulate and chemical emission levels need to maintain at an acceptable level
- Need to pre-treat the waste. Ex- It is required to remove the moisture content in oily sludge
- Using the auxiliary fuel for startups or using in afterburners

2.4.1 Power generation

The most common system used for power generation is the steam turbine drive with the steam generated from the waste heat. The function of the waste heat boiler included in the waste to energy system is to generating steam to drive the steam turbine. This steam turbine is coupled to a generator to produce electricity. New technologies developed to generate electricity directly from heat such as thermoelectric and piezoelectric generation.

Considering the power generation from waste heat it needs to consider the thermodynamic limitations at different temperatures. Because the effectiveness of the power generation from waste heat is depending upon the temperature of the waste heat source. The waste heat source is limited to medium temperature (250^0C – 650^0C) and high temperature (650^0C and higher) heat sources [62]. For the medium and high-temperature waste heat recovery sources as exhaust from gas turbines, exhaust from reciprocating engines, incinerators, and furnaces thermal conservation technology will be the traditional steam cycle [63].

2.4.2 Heat recovery steam generator

Heat recovery steam generator (HRSG) is a heat exchanger that is used to recover the energy from the high-temperature exhaust gas stream from a process. This system is complex. Because it consists of three heat recovery units which installed in it. They are evaporator, superheater, economizer, and steam drum. From the installed units, the absorbed waste heat will convert the waste energy to steam. The generated steam can be used for core generation. The hottest gas steam flows first through the superheater. Then the gasses are passed through the evaporator and economizer. Depend upon the exhaust gas flow, HRSG can be categorized into vertical and horizontal types. HRSG which is having a single pressure level with a one steam drum is a single pressure HRSG. In multi pressure HRSG, there are two or more pressure levels. The hottest flue gas is flowing first through the highest pressure likewise the lowest pressure level closer to the stack and there are more stream drums as there are pressure levels in the HRSG.

(I) Economizer

The economizer is located next to the evaporator where the exhaust gas having the lowest temperature. This unit was absorbing the flue gas energy and the feed water was heated up to the temperature of the saturated water. Heated water inside the economizer next flows to the boiler drum. If a boiler is equipped with an economizer the efficiency increases by 82%. This will lead to lower fuel costs. The difference between the water exit temperature from the economizer and the saturated water temperature is generally named as approach temperature difference. This temperature is typically designed to avoid the steam formation and water hammer in the economizer [64].

(II) Evaporator

Feedwater coming to the evaporator further heats up and steam generation occurs. Inside the economizer, phase change occurs in the entire water mass from liquid to steam. In the HRSG the evaporator is always installed in the middle position and the temperature of the gas is greater than in the economizer. In the evaporator, the feed water absorbs the required energy which required to change the water to steam. In the evaporator, the pinch point temperature difference is very small between two streams. This smaller pinch point results in increased steam power and the evaporator area will be large. Vice versa if the pinch point result is larger, the evaporator area will be less as well as the cost of the evaporator. The pressure drop of the flue gas is normally keeping at 25-40 mbar [64].

(III) Superheater

Since the steam leaving from the evaporator is saturated, it is further required to make superheated steam. To achieve this requirement, superheater is required. The superheater is placed in a way that more energy is in the superheated steam. Hence, it provides more energy for the steam turbine for the expansion in its first stage. And it should be closer to the isentropic expansion without condensation. Superheating could be parallel or counter flow type. If superheater is used for low or high heat applications economic consideration should be needed since the high cost of metal alloys are using for heat exchanger [65]

2.4.3 Waste heat recovery-based power generation

To recover the waste energy, Heat Recovery Steam Generator (HRSG) is used widely to generate power. Sometimes it was used as a generator for process heat in some industries, but the main role of the HRSG was cogeneration. Several researchers have researched steam generation from waste heat recovery using HRSG [66].

Below mentioned figure number 08 showing a concept of waste to energy using a HRSG to recover the waste heat using an economizer, an evaporator, and a superheater. The steam generated in HRSG is then expanded via a steam turbine to generate electricity.

The second law of thermodynamics to inspect the performance of the HRSG have used in the previously conducted researches. The performance was observed for various operating conditions of the HRSG as flue gas composition, pinch point temperatures, flue gas inlet temperatures, and the specific heat. This was guided to design a waste heat recovery-based power station effectively [67].

The concept of waste heat recovery-based steam generator (HRSG) with an economizer, evaporator, and superheater included in the simplified Rankine cycle as follows,

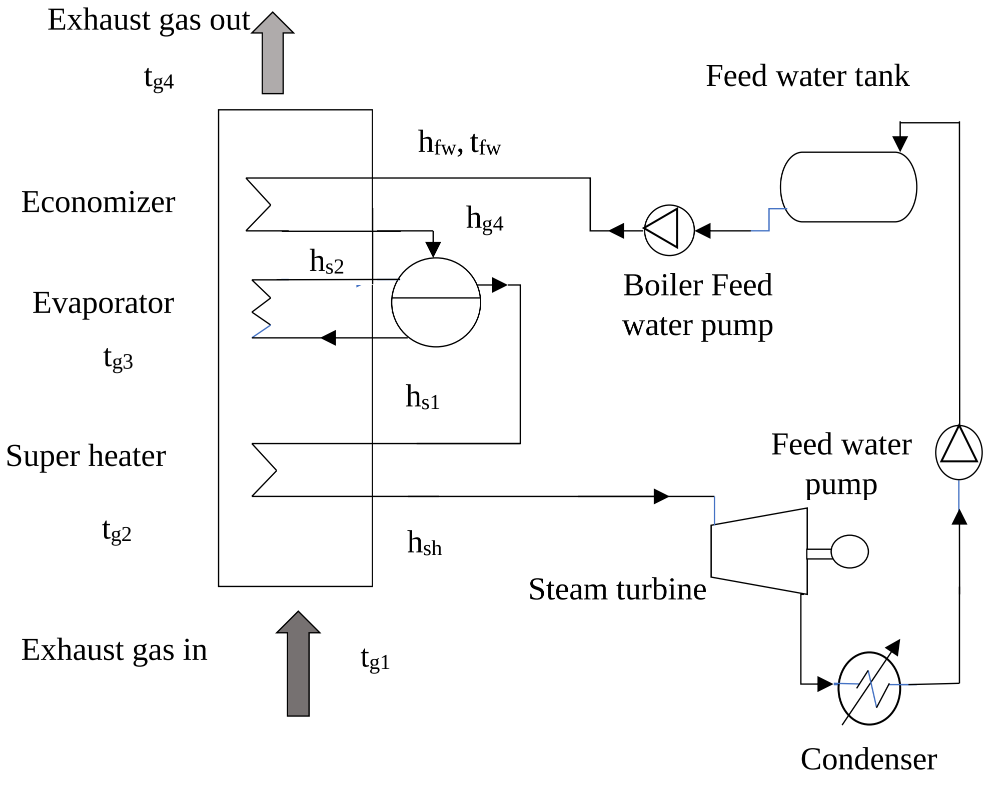

Figure 8: Concept of waste heat recovery-based power generation system [68]

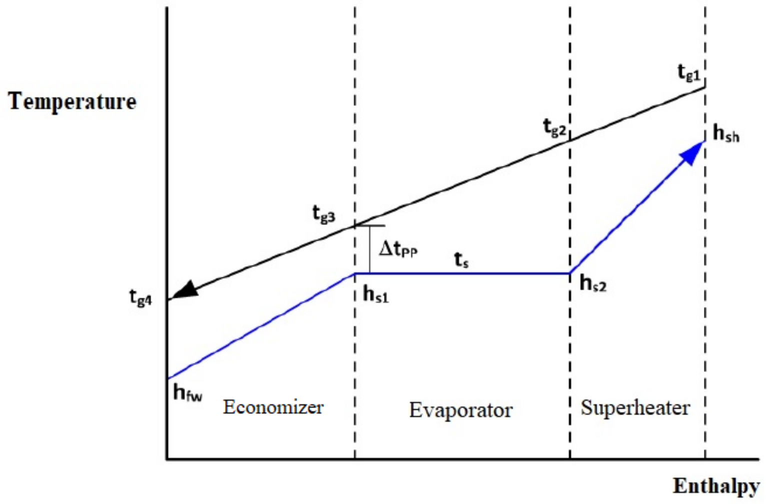

Figure 9:Typical temperature profiles for a single-pressure HRSG *[68], [69].*

Figure 09 shows a temperature profile for the water and steam in the HRSG. As for figure 08, exhaust gas is entering the superheater at t_{g1} and flows through the evaporator, then the economizer. Finally, the flue gas is exiting at t_{g4} temperature to the atmosphere. The feed water entre the economizer at a temperature of t_{fw} and sensibly heated up to t_{app} , and enter into the evaporator. Water boils in the evaporator at the saturation temperature of water t_s and enters the superheater as saturated steam and there it superheated to t_s to t_{sh}. Finally, the superheated steam entre to the steam turbine for the power generation.

In a temperature profile, when the difference of the temperatures of hot and cold fluids are at a minimum value; that location in the temperature profile was called the pinch point temperature.

Relative to the HRSG, pinch point temperature is the temperature difference of flue gas leaving temperature from the evaporator and temperature of the saturated steam. The approach point is the difference between the temperature of the saturated steam and the temperature of the water entering the evaporator. The size of the superheater and the evaporator are depended upon the pinch point temperature and the approach point temperature. These variables are selected based on the exhaust gas conditions [66].

Considering figure 09, the approach points and pinch points are directly affecting the production rate of the steam and steam temperature profiles

Below mentioned assumptions were made for the analysis,

- The system is in steadiness
- Negligible pressure drops in the steam side.
- Pressure drop in the flue gas doesn't influence its temperature and the approach point is negligible.

(I) Thermodynamic analysis

Pinch point temperature,

$$\Delta tpt = t_{g3} - t_S \qquad \text{Equation - 6}$$

The temperature difference between the saturated steam and the temperature of the water which enters the evaporator was the approach point temperature.

$$\Delta t_{app} = t_S - t_{Fw2} \qquad \text{Equation - 7}$$

These variables are directly controlling the size of the superheater and the evaporator. Hence the selection of pinch point temperature and the approach point temperature for the economical size of a HRSG was usually in the range of 8°C to 16°C [70]

The heat losses form small HRSGs to bout 2% and 0.5% in large HRSGs. For steam generation to occur, two conditions must be satisfied [71]

$$t_{g3} > ts \qquad \text{Equation - 8}$$

$$t_{g4} > t_{Fw1} \qquad \text{Equation - 9}$$

Using the temperature profiles for the HRSG (figure 09),

From equation (2),

Gas temperature entering the economizer $= t_{g3}$

$$t_{g3} = t_S + \Delta tpp$$

Where t_s is found in a water-steam property table for water saturation tables at the required pressure.

Applying the energy balance between t_{g1} and t_{g3}, evaporator exit temperature could be found.

$$m_{st} (h_{shs} - h_{apr}) = m_{gs} . C_{pg} . (t_{g1}-t_{g3}) \quad \text{Equation -10}$$

Where,

m_{st}	- Mass flow rate - steam
M_{gs}	- mass flow rate - gas
C_{pg}	- Value of specific heat - flue gas
t_{g1}	- Value of flue gas temperature - inlet to HRSG
t_{g3}	- Value of flue gas temperature -evaporator exit
h_{shs}	- Value of enthalpy - steam turbine inlet
h_{appr}	- Value of enthalpy of water at the inlet of evaporator

Heat balance for the steam turbine,

$$m_{St} . (h_{Shs}-h_{ouis}). h_{Stm} = P_{Stm} \quad \text{Equation - 11}$$

Where,

P_{stm}	- Steam turbine power output
h_{ouis}	- Value of enthalpy - steam turbine out
M_{st}	- Mass flow rate - steam
h_{shs}	- Value of enthalpy – (super-heated) steam
h_{stm}	- turbine mechanical efficiency

Enthalpy of steam at the turbine outlet,

$$h_{ou} = h_{shs} - h_{is}(h_{shs}-h_{ouis}) \quad \text{Equation - 12}$$

Where,

h_{ou}	- Value of enthalpy (steam) -turbine out
η_{Is}	-Turbine - isentropic efficiency
h_{ouis}	- Value of enthalpy (steam)- isentropic enthalpy

$$h_{apr} = C_P(t_S - t_{pt}) \quad \text{Equation 13}$$

Where,

C_p - Value of specific heat capacity of water at the turbine inlet

t_s - Value of enthalpy saturation temperature of water

h_{apr} - Value of enthalpy (approach point temperature)

t_{pt} - Pinchpoint temperature difference

The temperature in the stack. Applying heat balance of the whole HRSG

$$m_{gs} .C_P .(t_{g1}-t_{g4})(1-h_{lo}) = m_{st} . (h_{shs}-h_{sw}) \quad \text{Equation - 14}$$

Where,

t_{g1} - Value of enthalpy temperature - flue gas to the intel of HRSG

h_{sw} - Value of enthalpy - saturated water

h_{lo} - Heat loss from the HRSG

Heat balance for the economizer,

$$m_{gs}C_P(t_{g3}-t_{g4}) = m_{st}(h_{apr}-h_{sw}) \quad \text{Equation - 15}$$

Where,

m_{gs} - Flue gas - mass flow rate

C_p - Flue gas- specific heat

t_{g3} - Value of the temperature of the flue gas- after evaporator

t_{g4} - Value of the Flue gas out temperature

m_{st} - steam mass flow rate

h_{apr} - Enthalpy - approach point (temperature)

h_{sw} - Feed water enthalpy

Heat balance – Evaporator

$$m_{gs}C_P(t_{g2}-t_{g3}) = m_{st}(h_{s2}-h_{appr}) \quad \text{Equation - 16}$$

C_p - Flue gas- specific heat

m_{gs} - Flue gas - mass flow rate

t_{g2} - Temperature of the flue gas, after the economizer

t_{g3} - Temperature of the flue gas, after the evaporator

h_{s2} - Steam enthalpy- after the evaporator

h_{appr} - Enthalpy - approach point (temperature)

Heat balance -superheater

$$m_{gs}C_P(t_{g1}-t_{g2}) = m_{st}(h_{shs}-h_{s2}) \quad \text{Equation - 17}$$

C_p - Flue gas- specific heat

m_{gs} - Flue gas - mass flow rate

t_{g1} - Value of temperature of the flue gas, at the inlet of HRSG

t_{g2} - Value of temperature of the flue gas, after the economizer

h_{s2} - Value of steam enthalpy- after the evaporator

h_{shs} - Value of enthalpy – superheated steam

2.5 Research gap

Thermal oil-based power generation supplies 44 % total energy requirement of the country. Oily sludge is the main process waste from the oil-based thermal power stations, which is considered as a hazardous waste. Removal and disposal of oily sludge is expensive. Therefore, proper economic solution is required for disposing this generated oily sludge or reuse in an environmentally-friendly manner.

The present method used to eliminate the oily sludge was incineration which is an expensive method to eliminate the generated sludge. If the thermophysical properties in the oily sludge were investigated, there would be an opportunity of reusing the sludge economically. The possibility of using it as a fuel for co-generation could be investigated.

If suitable waste heat recovery technology could be applied to harness the waste heat from the incineration, a possibility will be there for micropower generation via incineration of oily sludge.

3.0 DATA COLLECTION AND ANALYSIS

As a case study, Uthuru Jnani Power Station was selected to evaluate the heat recovery options from the generated oily sludge. To investigate the waste heat recovery options, it is needed to investigate the quantity of the sludge generated from the power station as process waste of energy generation. Furthermore, it is required to investigate the thermophysical properties of the waste sludge to determine the usability of the sludge.

3.1 Data collection method

Initially, it was required to investigate the sludge generation quantity and the rate of sludge generation per day. Using the operational data at the power station, the actual sludge generation cannot be obtained directly. The only data which was monitored by the operational logs was the deviation of the level in the sludge tank. To calculate the total sludge generation, it was required to obtain the sludge incinerated data too. By combining both values, actual sludge generated potential could be obtained.

To investigate the sludge generation data, sludge tank level deviation data, and volume of incinerated sludge data were collected for two years. Furthermore, received heavy fuel oil quantity for the power plant, received fuel reports, and energy generation reports for two years were collected to study the constituents in the received fuel and estimate the sludge generation with the variation of the constituents in the received fuel oil. Therefore, to investigate the sludge generation, following data were collected for two years.

- Sludge tank level deviation
- The volume of incinerated sludge
- Energy generation reports
- Received heavy fuel oil quantity
- Received fuel reports

To study the sludge generating pattern and the constituents in the received fuel, below mentioned data were collected from the log sheets of operational data in the Power Station

- The Heavy Fuel Oil order quantity records for two years
- The sludge tank level reading (daily basis) for two years

- Measured the sludge incinerated volume (daily basis) for two years
- The fuel reports which received to the Power Station for two years
- The energy generation data for two years

To compare the aspects of utilization of generated oily sludge other than incineration, the sludge generation data at Sapugaskanda Power Station was considered as a case study to study the market value of the sludge. Hence, sludge sold data and the sludge generated sludge data at Sapugaskanda Power Station were collected. All the collected data were attached in Appendix A.

3.1.1 Laboratory results

To analyse the thermophysical properties of the generated sludge in Uthuru Janani Power Station, consulted the available fuel testing laboratories available in Sri Lanka. The laboratory of the Ceylon Petroleum Storage Terminal Ltd (CPSTL) is only equipped with relevant equipment to carry out the testing of the constituent and the calorific value testing for the sludge. The density of the given sludge sample was measured from the Asset Management lab in the generation division of the Ceylon Electricity Board and the value was 960 m^3/kg.

Below mentioned table no 05 represents the received test results for the given sludge sample from the laboratory of the Ceylon Petroleum Storage Terminal Ltd.

(The received report attached in Appendix -B)

Table 5:Properties of the sludge sample

Lab	Characteristic	Unit/test method	Value
CPSTL	Calorific value	ASTM D 240-17 (kcal/kg)	5066
	Ferrous (Fe)	Ppm / IP 501/05	117
	Vanadium (V)	Ppm / IP 501/05	12
	Aluminum (Al)	Ppm / IP 501/05	244
	Silicon (Si)	Ppm / IP 501/05	182
	Calcium (Ca)	Ppm / IP 501/05	368
	Phosphorus (P)	Ppm / IP 501/05	8
	Zinc (Zn)	Ppm / IP 501/05	18

3.1.2 Market Value for the Sludge

Though Uthuru Janani Power Station (UJPS) project was completed in the year 2012, any significant industrial organizations are not yet established in the northern Peninsula comparatively to the western part of the country. In the early stages, the generated sludge was incinerated inside the power station due to the unavailability of a buyer or an organization for the generated sludge in the northern peninsula. Later, competitive bids were called for selling the generated lube oil and sludge in 2015. UJPS was succeeded only to sell the used lube oil for a price of Rs.41.00 rupees for a liter. Still, there aren't any buyers with the necessary certification to buy the sludge as well as lube oil. Hence, there is no any other option than the incineration of generated sludge.

As the case study, Sapugaskanda Power Station was selected to study the market value of the generated sludge. Sapugaskanda Power Station is similar to Uthuru Janani Power Station in that the fuel which is used to generate electricity and the auxiliaries which were installed. The first, large scale power station which connected to the national grid was the Sapugaskanda power station belongs to CEB. This power station consists of two stations; namely station A and station B, the former being the older. In the station- "A" original equipment manufacturer is Pielstick which was commissioned by 1984 has operated more than 140,000 running hours. Here for the case study, selected station A because plant B was equipped with an incinerator and burning the generated sludge.

From the beginning, the generated sludge is being sold in the station A. Because plant A doesn't equip an Incinerator. Hence the generated sludge quantity in Station A is already calculated for the selling purpose of the sludge. According to their data, the sludge generating rate was 1.14 % of the fuel purification in plant A, when the engines are in continuous operation.

The variation of sludge generation pattern of the Sapugaskanda Power Station and the Uthuru Janani Power Station is presented in the below-mentioned figure no 10, on the next page.

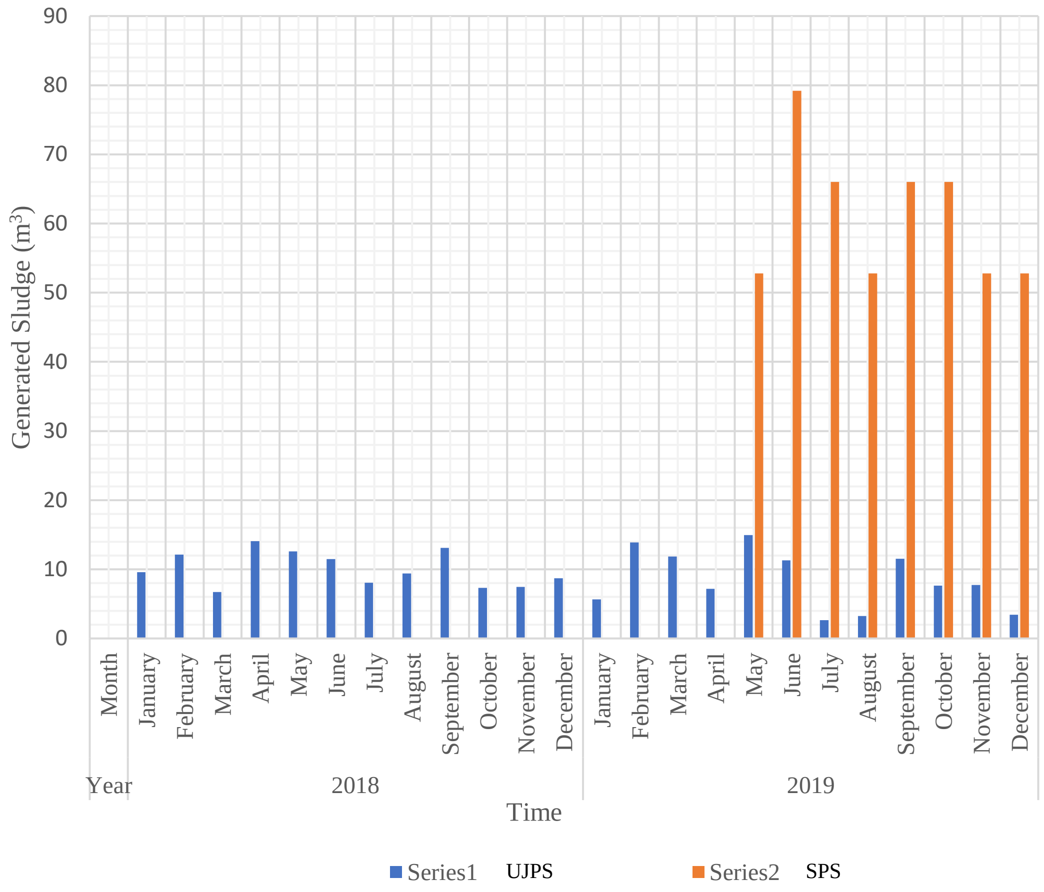

Figure 10: Generated sludge at Sapugaskanda and Uthuru Janani Power Station

Above figure 10, representing SPS (Sapugaskanda Power Station) sludge generated data from 2019 May to December. Hence, comparison could be done for this period. The generated sludge at Sapugaskanda was more compared to Uthuru Janani Power Station. Comparatively for this period UJPS, sludge generation was 62.451 m^3 and SPS, 488.4 m^3. The operating cost of the Incinerator for this sludge quantity will be nearly 3.1 Million. And by selling 5.3 Million was earned by SPS. (Appendix A)

3.2 Development of the Model

Considering the properties of the sludge as the initial step, the model can be developed to investigate the feasibility of using the generated sludge as fuel to a boiler. Hence investigate the possibility of operating a sludge-fired boiler to generate steam for a micropower generation.

As the second step, the model can be developed to investigate the feasibility of using the generated sludge as fuel to a hot water boiler and investigate a relationship between the generated sludge vs the hot water potential.

As the third step, the possibility of waste heat recovery by the incineration of the oily sludge can be investigated. Possibility of micropower generation can be investigated. By modeling a suitable HRSG to the incinerator, the possibility of harnessing the waste heat for micropower generation can be investigated.

3.2.1 Power generation

It is required to investigate the energy potential of oily sludge whether it is possible to use it as a fuel. This could be obtained by testing the calorific value of the sludge and its constituents. Then, it is required to select a suitable micro steam turbine to decide the required pressure and temperature values to maintain in the steam boiler fueled by the sludge.

A calculation was conducted considering the required condition of the steam for the turbine inlet and outlet, required mass flow rate of steam, the calorific value of the sludge, and the density of the sludge to find out the fuel requirement for the boiler to cater to the required condition. Using the Engineers Equation Solver, the developed model was optimized.

As for the technical data provided by the micro steam turbine manufacture, the requirements for the steam boiler was kept as follows, (Appendix C)

Steam inlet pressure = (35- 4) bar Steam Temperature = 350^{0}C -130^{0}C
Steam Out pressure = (1.1- 6) bar Steam out temperature = 315 ^{0}C- 105^{0}C
Required steam mass flow rate = 1.1 - 20 ton/hr
The supplied data for steam inlet for the turbine is in super-heated region.

From the steam tables,

T_{sat} = 242.5 ^{0}C , hg= 2836.0 kJ/kg , Boiler efficiency = 0.8 [ηb]

Density of sludge β = 960.0 kg/m^3;

Gross calorific value of sludge (C_v) = 21,196.14kJ/kg

Total heat required for 1kg of Super-Heated Steam = $h_g + C_p (T_{sup} - T_{sat})$

= 2836.0 +1.8 x (350-242.5)

= 3029.5 kJ/kg

Required mass flow rate (m^o) = 20 Ton /h

Required energy for 20 Ton/ h (Q_e) = 20,000 x 3073.0 kJ

From equation 2,

$$Q_E = \eta_B \, . M_F . C_V$$

Sludge requirement for 20 Ton (M_F) $= \dfrac{Q_E}{H_B \text{ x } c_V}$

$= \dfrac{20{,}000 \text{ x } 3029.5}{0.8 \text{ x } 21196.14}$

= 3573.17 kg

Required volume of fuel = M/β

$= \dfrac{3573.17}{960.0}$

= 3.72 m^3/h

Required fuel (as sludge) for a day = 3.72 m^3/h x 24 h

= 89.28 m^3

But average sludge generation per month at UJPS = 9.23 m3

From the above calculation,

Average sludge generation per day < Required sludge per day to run steam turbine

It is observed that the above requirement cannot be catered by the generated sludge quantity since it is less than the required sludge quantity to run the steam turbine.

(I) Optimization

As the optimizing parameters considered the mass flow rate of the steam turbine. As the initial step varied the mass flow rate of the steam to evaluate possible power output from the steam turbine. Trial runs were carried out using EES (Engineering Equation Solver software) to evaluate the possible power of the steam turbine which suit generating sludge.

Table 6: Sludge requirement for steam generation

Trial Run	**Mass flow rate (kg/h)**	**The volume of fuel required (as sludge) (m^3)**	**Turbine Power Output (kW)**
Run 1	10000	44.78	828.7
Run 2	12500	55.98	1036
Run 3	15000	67.18	1243
Run 4	17500	78.37	1450
Run 5	20000	89.57	1657
Run 6	22500	100.80	1864
Run 7	25000	112.00	2072
Run 8	27500	123.20	2279
Run 9	30000	134.40	2486

As the second step, the mass flow rate of the steam was kept at a minimum level and the steam pressure was changed (from 4 bar to 30 bar). Carried out Trial runs in EES. The received results are in table number 07.

EES calculation is attached in Appendix - C

Twenty-seven runs were conducted in EES to find the sludge requirement for a minimum mass flow rate of the steam which required for the selected steam turbine.

Table 7:Sludge requirement for a minimum mass flow rate of steam

Trial Run	Steam pressure (bar)	Steam mass flow rate (kg/s)	The volume of fuel required for a day M^3	Turbine Power output (kW)
Run 1	4	0.3056	5.177	62.78
Run 2	5	0.3056	5.165	73.63
Run 3	6	0.3056	5.153	82.46
Run 4	7	0.3056	5.142	89.91
Run 5	8	0.3056	5.131	96.34
Run 6	9	0.3056	5.121	102.0
Run 7	10	0.3056	5.112	107.0
Run 8	11	0.3056	5.102	111.5
Run 9	12	0.3056	5.094	115.7
Run 10	13	0.3056	5.085	119.4
Run 11	14	0.3056	5.077	122.9
Run 12	15	0.3056	5.068	126.1
Run 13	16	0.3056	5.060	129.1
Run 14	17	0.3056	5.052	131.9
Run 15	18	0.3056	5.045	134.5
Run 16	19	0.3056	5.037	137
Run 17	20	0.3056	5.030	139.3
Run 18	21	0.3056	5.022	141.5
Run 19	22	0.3056	5.015	143.6
Run 20	23	0.3056	5.008	145.5
Run 21	24	0.3056	5.001	147.4
Run 22	25	0.3056	4.994	149.2
Run 23	26	0.3056	4.987	150.9
Run 24	27	0.3056	4.980	152.5
Run 25	28	0.3056	4.974	154.1
Run 26	29	0.3056	4.967	155.6
Run 27	30	0.3056	4.961	157.0

From the above table 07, the required sludge quantity was varied between 5.177m3 to 4.961 m3 per day operation.

Based on the above analysis, rate of generated sludge as a fuel is not sufficient to run a steam turbine continuously.

3.2.2 Hot water generation

Hot water parameters were selected considered to same hot water parameters at Sapugaskanda Power Station.

pressure to 4 bar; temperature to 140 ^{0}C; water at room temperature = 27 ^{0}C;

C = 4.2 kJ/kg; efficiency η = 0.68; M = mass of water (1kg)

From the steam tables,

Saturation temperature of water at 4 bar = 143.6^{0}C, h_f = 604.65 kJ/kg

EES calculation was attached in Appendix -C

Energy required for to raise up the temperature of water = m x C x (t_1-t_2)

= 1 x 4.2 x (100-27)

= 306.6 kJ

1kg water to reach up to 140 ^{0}C = 604.65+ 4.2 x (140-100)

= 772.65 kJ

From equation (2) Total energy (Q_e) = 306.6 kJ + 772.65 kJ

= 1079.25 kJ

= 257.83 kcal

Maximum possible potential of hot water mass = M_h

Maximum generation of sludge per hour (m_{sh}) = 12.76 kg/h

$$M_h = \frac{M_{sh} \times Cv \times \eta}{Q_E}$$

$$= \frac{12.76 \times 21196.14 \times .68}{1079.25}$$

= 170.5 kg/h

Burning of waste sludge, the maximum possible hot water mass flow rate can be obtained was 170.5 kg/h at a pressure of 4 bar and 140 ^{0}C temperature.

(I) Optimization

As the optimizing parameter, generated sludge mass flow rate were considered for the two years. Monthly energy potential for the generated sludge by producing hot water at 4 bar, 140 ^{0}C temperature was analysed using the EES program.

Twenty-four simulation runs were conducted to study the variation of hot water energy potential for generated sludge data, using the EES software. (Appendix D)

Table 8: Hot water energy potential for generated sludge quantity

Trial Run	**Sludge generation per hour Kg/h**	**Hot water mass flow rate Kg/h**	**Hot water mass flow rate (per day) m^3**
Run 1	12.76	170.5	4.09
Run 2	16.18	216.2	5.19
Run 3	8.927	119.2	2.86
Run 4	18.74	250.3	6.01
Run 5	16.79	224.2	5.38
Run 6	15.3	204.4	4.91
Run 7	10.72	143.2	3.44
Run 8	12.52	167.3	4.02
Run 9	17.44	233.0	5.59
Run 10	9.76	130.4	3.13
Run 11	9.933	132.7	3.18
Run 12	11.61	155.1	3.72
Run 13	7.547	100.8	2.42
Run 14	18.52	247.4	5.94
Run 15	15.80	211.1	5.07
Run 16	9.573	127.9	3.07
Run 17	19.93	266.3	6.39
Run 18	15.04	200.9	4.82
Run 19	3.547	47.38	1.14
Run 20	4.307	57.53	1.38
Run 21	15.33	204.8	4.92
Run 22	10.17	135.9	3.26
Run 23	10.33	138.0	3.31
Run 24	4.56	60.92	1.46

Each simulated run represents the amount of hot water potential for the generated sludge quantity. Considering the values, it is observed that a considerable amount of hot water could be generated from the generated sludge quantity. The average hot water mass flow rate was computed as 3.94 m^3/day.

3.2.3 Heat recovery steam generator

Waste heat recovery option for the existing incinerator installed at Uthuru Janani Power Station to eliminate the sludge as the existing available sludge treatment method was considered. A model was developed to analyse the heat recovery potential of the existing incinerator while incinerating oily sludge.

As the initial step, the potential of waste heat energy from the flue gas of the incinerator "Detegesa-Delta IRLA 100" was investigated. The earlier investigated calorific value of the sludge for the calculation process to investigate the theoretical waste energy potential of flue gas of the incinerator was used.

Waste heat recovery from the incinerator flue gas could be achieved using a Heat Recovery Steam Generator (HRSG). For the modeling of HRSG , approach point , pinch point variables which directly link with the steam and steam generating rate were considered. To avoid the temperature cross situations, pinch point temperature was selected as 8^{0}C. HRSG, optimization could be done via Engineers Equation Solver (EES) software to get the maximum possible power output by harnessing the waste energy in flue gas of the incinerator to the HRSG. Several simulations were carried out in the EES software to analyse the power out from the HRSG.

The second set of simulations were conducted in the EES software to investigate optimum steam pressure in the Heat Recovery Steam Generator. This was achieved by keeping the pinch point temperature as a constant throughout the entire trial runs at 80C. For the analysis varied the steam pressure in the trial runs from 4 bar to 20 bar. The maximum power output will depend upon the sulfur dewpoint temperature at the HRSG exit, with consideration to the temperature of the flue gasses leaving from the HRSG. The net power out was selected compared with the required steam mass flow rate of the practically available steam turbines in the market.

(I) The waste heat recovery potential of flue gas

Waste energy potential of flue gas of the incinerator needed to be investigated, before proceeding further [72], (Appendix – F)

Measured values of the sludge a follow,

Calorific value of the sludge = 5066 kcal / kg = 21196.14 kJ/kg

Density of the fuel (β_f) = 960.0 kg/m^3

From the operational data and the manual of the installed incinerator, the following data was used.

Exhaust gas temperature = 282 ^{0}C (Appendix F)

Mass flow rate of sludge (m_f) = 150 l/h

= 144 kg/h

From equation no- (3)

The energy given by the fuel (Q_f) = $m_f \cdot C_v$

Q_f = 144 .0 x 21,196.14 kJ/h

= 3052.24 MJ/h

Density of the flue gas = 1.35 Kg/Nm^3 [73]

Mass flow rate of flue gas (m_g) = 17,280 kg/h

Flue gas out temperature from HRSG (t_{go}) should be the lowest temperature in the HRSG system. The value of the t_{go} should be more than the dew point temperature of Sulphur. And it was assumed that Sulphur content in the sludge is equal to Sulphur content in the fuel which is normally deviating between 1. 5- 4.5 (%m/m). Hence the Sulphur dew point [74] is 148 ^{0}C (Appendix E).

Hence, t_{go} taken as = 148 ^{0}C and t_{gi} taken as = 282 ^{0}C (Average exhaust gas temperature)

From equation (4),

The energy absorbed from the flue gas (Q_g) = m_g x C_{pg} x (t_{go}-t_{gi})

$= 17280 \times 1.05 \times (282 - 138)$

$= 2612.73$ MJ

From equitation (3),

Extracted energy percentage $= Q_{ex}$

$Q_{ex} = Qg/Qf$

$$= \frac{2612.73}{3052.24} \times 100\ \%$$

$= 85.06\ \%$.

From the above equations, the theoretical waste energy potential in the flue gas of the incinerator was 85.06 % by incinerating the generated sludge from the power station.

(II) Modeling a suitable HRSG for the incinerator

A heat recovery steam generator (HRSG) is a heat exchanger between hot gases stream out from high-temperature flue gas source and demineralized water to produce high pressure and temperature steam for either for power generation or any other process works. Selecting the starting point of the HRSG, the main thing that needs to be verified is the steam-generating capacity and the temperature profiles of the steam [75]. By selecting the desired steam flow rate, exit gas temperature, and the required mass flow rate, a conventional steam generator can be operated to achieve the required steam demand. Furthermore, due to the large gas/steam ratio, low inlet gas temperatures in the unfired mode, HRSG performs differently.

By considering the above, knowing the exhaust gas flow, temperature, gas analysis, and steam parameters, can establish gas–steam temperature profiles and duty of each section such as a superheater, evaporator, and economizer in the design mode, as for figure 8.

It is not necessary to be familiar with the geometry shape of the HRSG to evaluate its performance [76] Two variables that directly affect steam production and the gas and steam temperature profiles are the pinch point and the approach point as in Figure 9.

Size of the superheater, evaporator, and economizer depend upon the selection of pinch point temperature and approach point temperature. The pinch and approach points for unfired HRSGs are usually in the range of 7 °C to 25 °C [75].

In this design calculation, the approach point temperature difference was selected as 8^0C. Then there should be two conditions which should be satisfied as $t_{g3}>t_s$ and $t_{g4}>t_{fw}$.

By simulating the HRSG, effectiveness of HRSG with different gas inlet conditions can be analysed. And also, it will help to optimize the temperature profile. Considering the above situation, power out from the steam turbine could be optimized using the Engineering Equation Solver.

(III) Optimization

The temperature profile of the HRSG is as for the below-mention figure 9.

Temperature profiles for a single-pressure HRSG

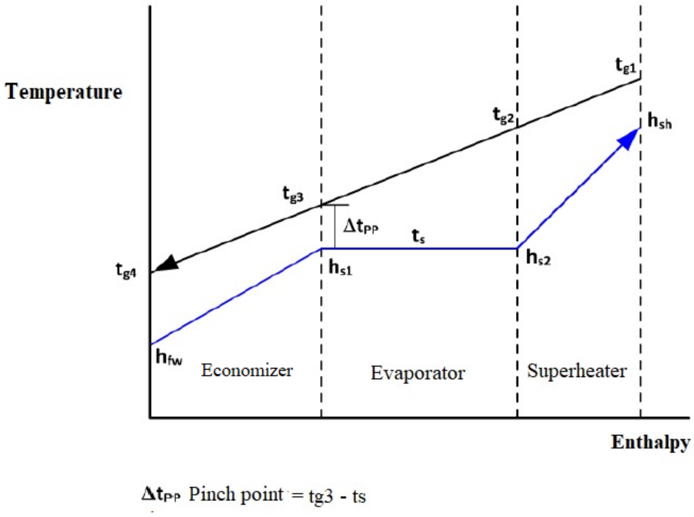

Figure 9:Typical temperature profiles for a single-pressure HRSG

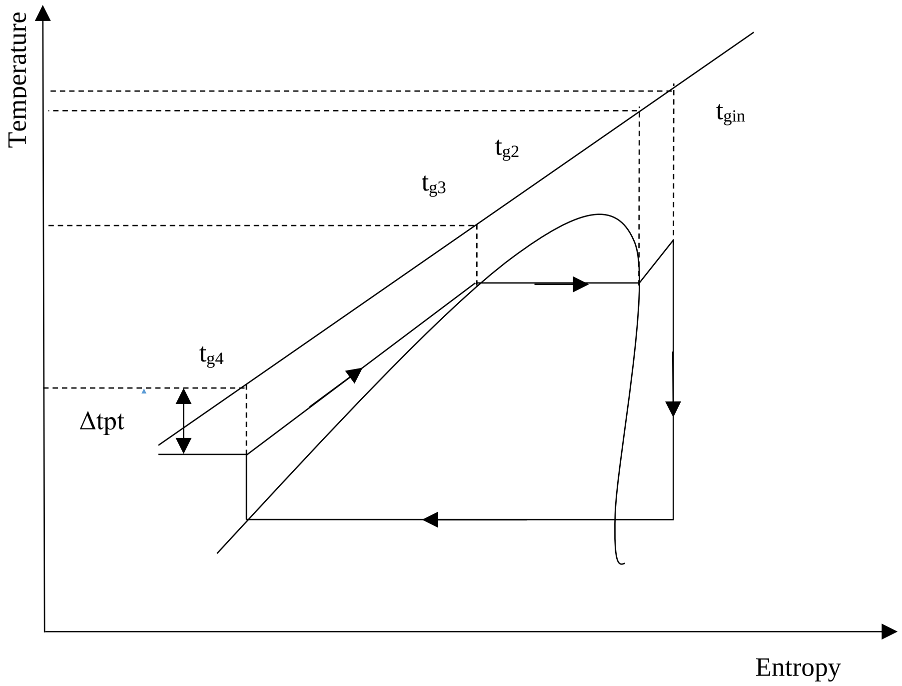

Figure 11:Rankine cycle [77]

Optimizing parameters

Following parameters were assumed for the calculation

Inlet parameter of the steam was taken as 16 bar and 280°C

The pressure in the condenser (p_{out}) = 1.1 bar

Steam turbine power output (P_{stm}) = 90 kW (Appendix B)

Isentropic efficiency of the steam turbine (η_{stm}) = 0.93

Mechanical efficiency of the steam turbine (η_{me}) = 0.98

HRSG, approach temperature (Δtppt) = 8^0C

Value of heat losses (h_{l0}) from the HRSG to surrounding = 0.02 [75]

Following calculation process was carried out to make the parameters to optimum level while not affecting the plant operation. Keeping these conditions satisfactorily the possible stream turbine output in kW and the temperature difference for pinch point was taken in Celsius.

Pinch point temperature difference = Δtppt = 8^0C

From the equation (6),

$$\Delta t_{pt} = t_{g3} - t_s$$

Where, t_s = 201.37 ^{0}C at 16 bar saturation temperature.

From equation (10); energy balance applies to: t_{g1} and t_{g3};

$$m_{St}\,(h_{shs} - h_{apr}) = m_{gs}\,.\,C_p\,.\,(t_{g1}\text{-}t_{g3})$$

$$m_{st} = \frac{M_{gs}\ X\ C_p\ x\ (t_{g1}\text{-}t_{g3})}{(h_{shs} - h_{apr})}$$

The variables in the above equation no (10), $t_{g3,}$ and m_{st} both are unknown. To evaluate the value of t_{g3} the value of m_{st} should be known. Hence, to find the value of m_{st} heat balance can be applied for the steam turbine.

From equation no (11); applying heat balance to the turbine,

$$m_{St} \cdot (h_{Shs} - h_{ou}) . h_{me} = P_{stm}$$

$$m_{st} = \frac{P_{stm}}{(h_{shs} - h_{ou}) \times \eta_{me}}$$

From equation no (12), isentropic outlet enthalpy,

$$h_{ou} = h_{shs} - h_{stm}(h_{shs} - h_{ouis})$$

$$h_{stm} = \frac{h_{shs} - h_{ou}}{(h_{shs} - h_{ouis})}$$

Finding the h_{ouis} value in equation (12),

$S_{hs} = S_{out} = 6.8059$ (Isentropic) - at 16 bar -280 ^{0}C temperature, entropy values.

$S_{out} = S_f + x. S_{fg}$ (S_f = 1.3330 kJ/kgk, at 1.1 bar and S_{fg} = 5.9938 kJ/kgk)

Hence, $x = 0.9130$

$H_{outis} = h_f + x. H_{fg}$ (hf = 428.84 kJ/kg , at 1.1 bar and h_{fg} = 2250.3 kJ/kg)

Hnece, h_{outis} = 2,483.36 kJ/kg.

H_{shs} = 2990.10 kJ/kg (at 16 bar -280 ^{0}C temperature - enthalpy value)

From the equation no. (11),

$$\text{Steam mass flow rate } (m_{st}) = \frac{P_{stm}}{(h_{shs} - h_{ou}) \times \eta_{me}}$$

$$= \frac{90}{(2990.10 - 2518.83) \times 0.98}$$

$$= 0.194 \text{ kg/s}$$

From equation (13),

$$h_{apr} = C_p \; (t_s - t_{pt})$$

$$= 4.187 \, (204.3-8) \qquad = 821.9 \text{ kJ/kg.}$$

From equation (10),

$$t_{g3} \quad = t_{g1} - \left[\frac{m_{st}\ (h_{shs} - h_{apr})}{m_{gs} \text{ x } C_p} \right] = 210.38\ ^0C$$

From the equation (6),

The pinch point temperature difference $= \Delta_{tpt}$

$$\Delta_{tpt} = t_{g3} - ts$$

$$= 210.38\ ^0C - 201.37\ ^0C = 9.01\ ^0C$$

From the equation (14); applying heat balance to span over the whole steam cycle,

$$m_{Gs} .C_p .(t_{g1}\text{-}t_{g4})(1\text{-}h_{Lo}) \quad = m_{St} . (h_{Shs}\text{-}h_{Sw})$$

$$t_{g1} - t_{g4} = \frac{m_{st} \text{ x } (h_{shs} - h_{sw})}{m_{gs} \text{ x } C_p \text{ x } (1\text{-}h_{lo})}$$

Assuming that the specific heat is not changing from t_{g1} to t_{g4}.

Enthalpy of feed water was investigated after the condenser, saturated water at 1.1 bar. Neglected the liquid water enthalpy across the pump hence feed water enthalpy value at 16 bar pressure was the enthalpy after the condenser (saturated water)

Hence,

h_{shs} = enthalpy value (super-heated steam at 16 bar and 280 ^0C)= 2990.10 kJ/kg

h_{sw} = enthalpy of saturated water at 1.1 bar = 428.84 kJ/kg

From equation (14),

$$t_{g4} \quad = t_{g1} - \left[\frac{m_{st}\ (h_{shs} - h_{sw})}{m_{gs} \text{ x } C_p \text{ x } (1\text{-}h_{lo})} \right]$$

$$= 196.16\ ^0C$$

From the equation (15); applying heat balance to economizer,

$$m_{gs} C_p (t_{g3}\text{-}t_{g4}) \;=\; m_{st}(h_{apr}\text{-}h_{sw})$$

$$t_{g3}-t_{g4} = \frac{m_{st} \text{ x } (h_{apr}- h_{sw})}{m_{gs} \text{ x } C_p}$$

From the equation (16); heat balance over the evaporator,

$$m_{gs}C_p\left(t_{g2}-t_{g3}\right) = m_{st}(h_{s2}-h_{apr})$$

$$t_{g2}- t_{g3} = \frac{m_{st} \ (h_{s2}- h_{apr})}{m_{gs} \text{ x } C_p}$$

From equation (13), $h_{apr} = C_p \ (t_s-t_{pt})$

$$h_{apr} = 4.187 \text{ x } (201.37- 8)$$

$$= 809.64 \text{ kJ/kg}$$

From equation (16), $t_{g2} = t_{g3}+ \left[\frac{M_{st} \ (h_{s2}- h_{apr})}{m_{gs} \ xC_p} \right]$

$$= 277.14 \ ℃$$

When optimizing, the pinch point temperature should fall between 8^0C to 16^0C. If the obtained pinch point temperature results get closer to 8^0C ,the power output from the HRSG will be maximum.

But on the other hand, when power from HRSG higher mean, large scale size and the high cost will make the design inefficient. If the temperature value of pinch point gets closer to 16^0C, the power out from the heat recovery steam generator will be limited.

Flue gas out temperature from HRSG (t_{g4}) computed as 195.70 ^{0}C. There will be an opportunity of absorbing more energy from the flue gas.

To determine the possible power out from the HRSG, the steam pressure was selected to the steam pressure of 16 bar and 280 ^{0}C, used the EES software, and carried out simulation trial runs to study the maximum power output which could be obtained from the HRSG. (Other design parameters are kept the same – see appendix E)

Results obtained for the simulation trial run was as follow,

Table 9:Variation of turbine output power

Trial Runs	**P_{stm} KW**	**m_{st} Kg/s**	**t_{g1} ^0C**	**t_{g2} ^0C**	**t_{g3} ^0C**	**t_{g4} ^0C**	**t_{ppt} ^0C**
Run 1	50	0.1083	282	278.4	242	234.1	40.61
Run 2	55	0.1192	282	278.1	238	229.3	36.61
Run 3	60	0.13	282	277.7	234	224.5	32.61
Run 4	65	0.1409	282	277.3	230	219.7	28.61
Run 5	70	0.1517	282	277	226	214.9	24.61
Run 6	75	0.1625	282	276.6	222	210.1	20.61
Run 7	80	0.1734	282	276.3	218	205.3	16.61
Run 8	85	0.1842	282	275.9	214	200.5	12.61
Run 9	90	0.195	282	275.5	210	195.7	8.61
Run 10	95	0.2059	282	275.2	206	191	4.611
Run 11	100	0.2167	282	274.8	202	186.2	0.611
Run 12	105	0.2275	282	274.5	198	181.4	-3.39
Run 13	110	0.2384	282	274.1	194	176.6	-7.39
Run 14	115	0.2492	282	273.8	190	171.8	-11.4
Run 15	120	0.26	282	273.4	186	167	-15.4
Run 16	125	0.2709	282	273	182	162.2	-19.4
Run 17	130	0.2817	282	272.7	178	157.4	-23.4
Run 18	135	0.2925	282	272.3	174	152.6	-27.4
Run 19	140	0.3034	282	272	170	147.8	-31.4
Run 20	145	0.3142	282	271.6	166	143	-35.4
Run 21	150	0.325	282	271.2	162	138.2	-39.4

Where,

P_{stm} -Turbine power output

m_{st} - Steam mass flow rate

t_{g1} - Temperature in-superheater

t_{g2} - Temperature in-Evaporator

t_{g3} - Temperature in-Economizer

t_{ppt} - Pinch point temperature difference

t_{g4} - Exhaust gas temperature out from HRSG

From the above-obtained results, when the turbine power output is 90kW the pinch point temperature was indicated as 8.61^0C and the turbine power output is 95kW the pinch point temperature indicated as 4.611^0C. From the above analysis, it can be easily understood that HRSG optimizing is possible to gain significant power out between 90 kW to 95 kW using the waste heat of the incinerator. Hence, it is required to carry out the second analysis for the HRSG to find out the best suitable steam pressure of HRSG. This was achieved by keeping the pinch point temperature as a constant throughout the entire trial runs at 8^0C. For the analysis, steam pressure in the trial runs was varied from 4 bar to 20 bar. The Sulphur dew point at the exhaust of the HRSG was taken as the limiting factor for this analysis.

Table 10:Variation of steam pressure

Trial Runs	**P_{sh} Bar**	**t_{pt} C**	**t_{g1} C**	**t_{g2} C**	**t_{g3} C**	**t_{g4} C**	**P_{tur} KW**	**m_{st} Kg/s**
Run 1	4	8	282	266.8	151.6	141.5	80.25	0.3132
Run 2	5	8	282	268.2	159.8	148.5	87.08	0.298
Run 3	6	8	282	269.3	166.8	154.6	91.15	0.2847
Run 4	7	8	282	270.3	173	160	93.63	0.2728
Run 5	8	8	282	271.1	178.4	165	95.1	0.262
Run 6	9	8	282	271.9	183.4	169.6	95.84	0.2521
Run 7	10	8	282	272.6	187.9	173.8	96.04	0.2428
Run 8	11	8	282	273.2	192.1	177.8	95.8	0.2341
Run 9	12	8	282	273.7	196	181.6	95.24	0.2259
Run 10	13	8	282	274.2	199.6	185.2	94.41	0.2181
Run 11	14	8	282	274.7	203.1	188.6	93.36	0.2107
Run 12	15	8	282	275.1	206.3	191.9	92.14	0.2035
Run 13	16	8	282	275.5	209.4	195	90.76	0.1967
Run 14	17	8	282	275.9	212.3	198	89.27	0.1901
Run 15	18	8	282	276.2	215.1	201	87.67	0.1837
Run 16	19	8	282	276.6	217.8	203.8	85.98	0.1775
Run 17	20	8	282	276.9	220.4	206.5	84.21	0.1715

Where,

P_{sh}	Maximum steam pressure	t_{pt}	Pinch point temperature difference
t_{g1}	Temp in-superheater	t_{g2}	Temp in-Evaporator
t_{g3}	Temp in- Economizer	t_{g4}	Temp out -HRSG)
P_{stm}	Turbine power output	m_{st}	Steam mass flow rate

To analyse the sludge requirement with the power generation, input the above received results in table 10 to the EES. The received sludge requirement for the operation of the steam turbine for 93.63 kW power for a day 6.264 m^3 of sludge is required.

Table 11: sludge requirement with power generation

Trial Run	**Steam pressure (P_{sh}) bar**	**Turbine output (P_{tur}) kW**	**Fuel mass flow rate (m_f) kg/h**	**Fuel required for a day (V_{day}) m^3**
Run 1	4	80.25	289	7.225
Run 2	5	87.08	274.5	6.862
Run 3	6	91.15	261.9	6.546
Run 4	**7**	**93.63**	**250.6**	**6.264**
Run 5	8	95.1	240.3	6.008
Run 6	9	95.84	230.8	5.771
Run 7	**10**	**96.04**	**222.1**	**5.551**
Run 8	11	95.8	213.8	5.345
Run 9	12	95.24	206	5.151
Run 10	13	94.41	198.7	4.967
Run 11	14	93.36	191.6	4.791
Run 12	15	92.14	184.9	4.623
Run 13	16	90.76	178.5	4.462
Run 14	17	89.27	172.3	4.307
Run 15	18	87.67	166.3	4.157
Run 16	19	85.98	160.5	4.012
Run 17	20	84.21	154.9	3.872

Where,

P_{sh} - Steam pressure

P_{tur} - Steam turbine power output

m_f - Fuel mass flowrate

V_{day} - Sludge requirement for a day

3.3 Analysis

The main intention was to investigate the energy potential of the oily sludge, whether it is possible to use it as a fuel for micropower generation. It was achieved by using the generated sludge as fuel for a steam boiler and generating steam for the steam turbine. Sludge samples were tested for the calorific value and the metal contaminants. It was investigated that oily sludge is having nearly half of the calorific value of the fuel used for the power generation.

From the calculation, it was investigated that a huge amount of sludge is required for the micropower generation using the sludge as a fuel. This was because of the low calorific value in the oily sludge. That much the sludge generation is not feasible from the power station side.

Several simulation trial runs were conducted to analyse the sludge requirement. It was examined by varying the steam mass flow rate required for the turbine. The requirement of the sludge was varied from 44.78m^3/day to 134.40 m^3/day. The next analysis was conducted keeping the minimum mass flow rate of the steam as a constant and varied the pressure in the boiler to investigate the power that could be harnessed from the steam turbine with the required sludge quantity as fuel. Turbine output power was varied 62.78 kW to 157 kW. The volume of the sludge required was varied 5.177m^3/day to 4.961m^3/day. Based on this analysis the required sludge quantity is not generated by the power station compared with the sludge generating pattern investigated for UJPS for two years.

The feasibility of sludge used as a fuel to generate hot water was investigated. Selected the hot water pressure to 4 bar and temperature 140 ^{0}C with considering the same hot water parameters at Sapugaskanda Power Station. Hot water could be used to heat the fuel in the power station. From the calculation it was investigated that burning of waste oily sludge, the maximum possible hot water mass flow rate can be obtained is 170.5 kg/h at a pressure of 4 bar and 140 ^{0}C temperature.

Several simulations were carried out in EES software, considering the mass flow rate of the sludge for two years. The monthly energy potential was analysed as hot water from the generated sludge. It was noted that the average hot water mass flow rate for two years is $3.94m^3$/day. Generating hot water is a feasible scenario using the generated sludge. Using the optimized data an equation was derived for generated hot water vs sludge mass flow rate. The available maximum energy potential for known sludge quantity hence, can be analysed.

A graph of the sludge mass flow rate (S_h) vs maximum possible hot water mass flow rate (M_h) was plotted.

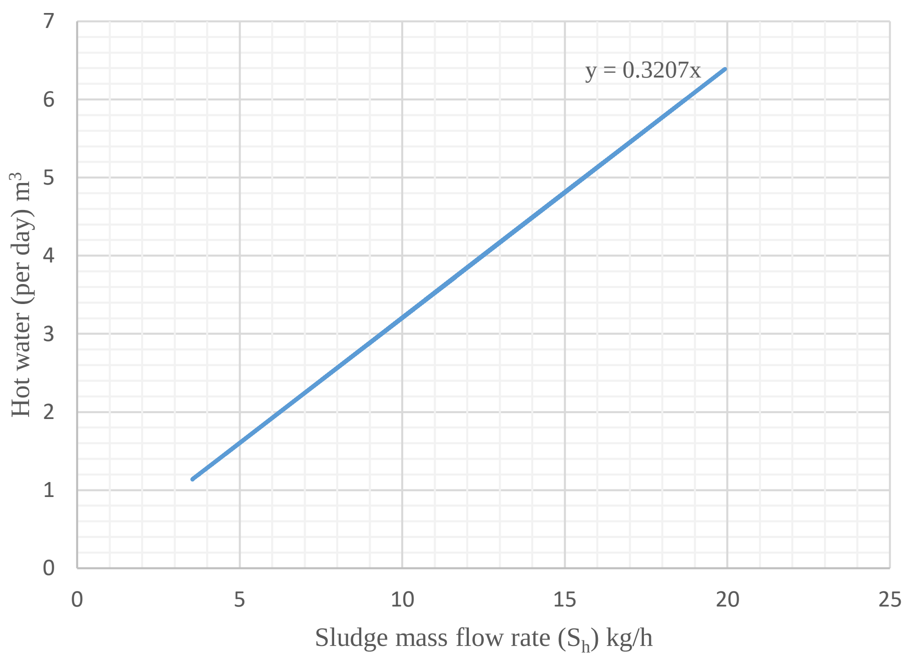

Figure 12: Generated sludge vs the generated hot water

Using the above equation of the graph, it will be easy to predict the maximum possible hot water flowrate for generated sludge at 4 bar, 140^0C.

The regression equation for the above graph is - M_h=0.3207S_h.

The waste heat recovery option for the existing incinerator installed at UJPS was considered as a case study. A model was developed to analyse the heat recovery potential of the existing incinerator that incinerate oily sludge. The theoretical waste energy potential from the exhaust gas in the incinerator was 85.06 % by incinerating the generated sludge from the power station. Therefore, a considerable heat recovery potential is available in the flue gas of the incinerator.

Considering the steam-generating potential, the desired steam flow rate, exit gas temperature, and the required mass flow rate, a conventional steam generator can be operated to achieve the required steam demand. By knowing the exhaust gas flow temperature, steam parameters, and gas–steam temperature profiles were analysed to model the HRSG. The necessary parameters were set up to optimize the HRSG.

Pinch point temperatures were set up to 8^0C. According to the simulation results, when the turbine power output was 90 kW, pinch point temperature was indicated as 8.61^0C. When the turbine power output was 95 kW, pinch point temperature was indicated as 4.611^0C. Based on these results, optimizing HRSG was possible to get the power output between 90 kW to 95 kW because the HRSG power output will be maximum when the pinch point temperature reaches 8^0C.

The second simulation was carried out by keeping the pinch point temperature at 8^0C and varied the steam pressure from 4 bar to 20 bar while the Sulphur dew point at the HRSG exit was taken as the limiting factor. Using the results obtained from the simulation trial runs, a graph of Steam pressure vs turbine power output was plotted to justify the optimization of the turbine power output.

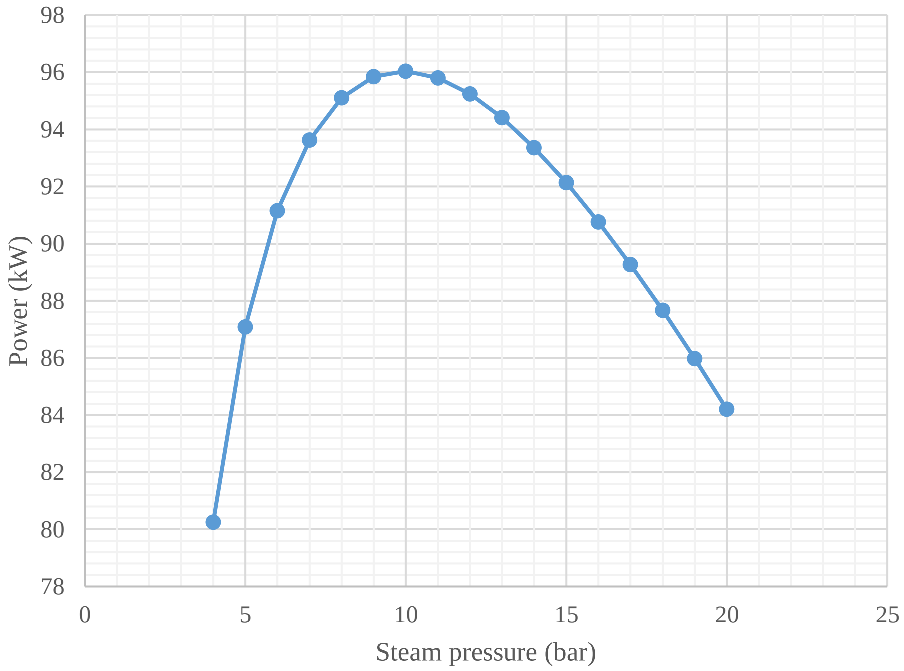

Figure 13:Steam pressure vs turbine power output

From the above figure 13, the maximum power output was identified as 96.04 kW. By comparing with the commercially available steam turbine technical data, the possible power output was 93.63 kW. For a day 6.264 m^3 of sludge is required to operate the steam turbine at 93.63kW.

3.3.1 Economic value for constituents

The results in table 12 represent the analysis of the constituents in the sludge. The economic value of the sludge was estimated according to this analysis.

Table 12:Properties of the sludge sample

Analysed metal	**Quantity (ppm)**
Ferrous (Fe)	117
Vanadium (V)	12
Aluminum (Al)	244
Silicon (Si)	182
Calcium (Ca)	368
Phosphorus (P)	8
Zinc (Zn)	18

Vanadium can easily be extracted from the fly ash of the sludge [32]. Using the data from the previously conducted research, the leaching and solvent extraction process are using to extract the vanadium from the sludge while burning and getting the fly ash. The efficiency of leaching is 65% while the efficiency of the solvent extract is 86%.

The below-mentioned calculation was based on the assumption of the vanadium quantity as 12mg/kg (12ppm) also include in the fly ash of the sludge.

Applying the above research data to analyse the extractable vanadium from the generated oil sludge,

The average of annual sludge generation = 110.8 m^3 = 109, 725 kg

Availability of vanadium quantity in the sludge = 109,725 x 12 $x10^{-3}$

= 1316.7 kg

Vanadium extracted to leaching solution = $1316.7 \times \frac{65}{100}$

= 855.86 kg

Estimated vanadium quantity that can be extracted annually = $855.86 \times \frac{86}{100}$

= 736.03 kg

Estimated vanadium quantity that can be extracted monthly = 61.35 kg

Market value of vanadium [78] = US$ 27/ kg

The economic value of the extracted vanadium per month = 61.35 x US$ 27

= US$ 1656.45

Economic value of the extracted vanadium per year = US$ 19,877.4

Economic value of the extracted vanadium per year (LKR) = Rs. 3,736,951.2

(Considered the Exchange rate of 1.USD to Rs. 188 LKR)

Yearly economic value is nearly LKR 37.3 Million for the extracted Vanadium.

4.0 RESULTS AND DISCUSSION

In this research work, sludge generating patterns in both powers stations was compared for eight months. Within this period oily sludge generation at UJPS was 88.3 m^3 and SPS, 488.4 m^3. The ratio of sludge generation for this period in UJPS to SPS was nearly 2:11.

The operating cost of the incinerator at UJPS was nearly 3.1 Million Rupees. While 5.3 Million Rupees was earned SPS by selling the sludge. Compared with the selling cost and the incinerate cost, the best option is selling the sludge. But analysing the sludge price variation for eight years as illustrated in figure 19, it is clearly shown that the market price was drastically declining. But there is a significant value in the market for the generated sludge. Since the value of the sludge depends on the bargaining power of the buyer, the price doesn't reflect the real value of the sludge which is an unnecessary burden for the CEB. Therefore, a profitable solution for CEB to handle this generated process waste from the energy generation by the thermal power stations without allowing the buyers to take advantage of it is required.

If there is any possibility of reusing the sludge or if there is a possibility of applying waste to energy option for the generated sludge it will be a profitable solution other than selling the sludge. Hence, the constituents in the sludge and its calorific value were investigated. The calorific value of the sludge was 5066 kcal/kg, which was nearly half of the fuel calorific value used for the power generation.

Since a considerable calorific value was available in the sludge, the feasibility of using the sludge as fuel was investigated in this work. Furthermore, investigated the feasibility of power generation from the sludge by using a micro steam turbine and the possibility of generating the hot water using the generating sludge. The modeling process was conducted using the Engineering Equation Solver (EES).

Thermodynamic calculations were computed to investigate the energy required to generate steam from the generated sludge. It was investigated that to generate 1 ton of steam; sludge 181.14 kg (0.1886 m3) was required.

The possibility of power generation by sludge fired boiler was considered. Several simulation trial runs were carried out by varying the steam pressure to the turbine. Examine the required mass flow rate of the fuel for different pressure conditions to the steam turbine inlet. The required sludge requirement was $44.78m^3$ to $134.40m^3$. The sludge generation rate was less than the required sludge amount to operate the sludge fired boiler. Hence the second set of simulation trial runs were carried by varying the steam pressure from 4 bar to 30 bar. Investigated the required mass flow rate varying from $5.177m^3$ to $4.961m^3$. The sludge generation rate by power generation was less than the required sludge amount to operate the sludge fired boiler.

The possibility of generation of hot water using the oily sludge as the fuel was considered. The required parameter of the hot water was assigned as 4 bar, 140 ^{0}C temperature. From the received results and as for the analysed results flow rate of hot water for a day was varied from 1.14 m^3 to 6.39 m^3. Per-day energy potential for the generated sludge by producing hot water was varied from 1.14 m^3 to 6.39 m^3. It was investigated that a considerable amount of hot water generation could be achieved as hot water from the generated sludge. Furthermore, an equation was derived to analyse the potential of hot water mass flow rate vs generated sludge. The equation was $M_h = 0.3207 S_h$; where M_h represents the hot water mass flow rate and S_h represents the sludge generation

Considering the above results, it was investigated that a higher sludge quantity was required for the power generation via a sludge-fired boiler with a micro steam turbine. It was not feasible to have a separate sludge-fired boiler or a hot water boiler as a solution for the generated sludge because sludge generation will depend upon thermal power generation.

Hence, the work was focused on the waste heat recovery from the sludge incineration using the existing incinerator at UJPS as a case study. As the initial step, the potential of the waste heat recovery in the flue gas of incinerator make of Detegesa-Delta IRLA 100 was investigated. The possibility of waste heat recovery was investigated as 85.06%.

Hence, modeling a HRSG for the incinerator flue gas to recover the energy from the sludge incineration was focused. The same software was used for the modeling process and flue gas exit temperature at the stack compared with the sulfur dew point temperature was considered the limiting factor. The pinch point temperature difference to be 8^0C was assumed for the modelling process. For the modeling process assumed and avoided the temperature cross situations in the temperature profile. As for the initial investigation, several simulation trials were conducted without considering the scope and cost of the HRSG to determining the probable power out.

Hence, to investigate the power out from the HRSG, the pressure of the steam was selected to 16 bar and 280 ^{0}C. From the received results when the turbine power output was 90 kW the pinch point temperature was indicated as 8.61^0C and the turbine power output is 95kW the pinch point temperature was indicated as 4.611^0C. Based on these results, optimizing HRSG was possible to get the power output between 90 kW to 95 kW because the HRSG power output will be maximum when the pinch point temperature reaches 8^0C. Based on this result, the second set of simulation trials to get the best steam pressure for HRSG were carried out. This was achieved by varying the steam pressure from 4 bar to 20 bar while keeping the pinch point temperature at 8^0C. The Sulphur dew point at the exhaust of the HRSG was taken as the limiting factor for this analysis.

From the received results the maximum turbine output was 96.04 kW with superheated steam at 10 bar in the EES simulation trial number 7. In this condition, the flue gas exit temperature from the HRSG was 173.8^0C which is greater than the Sulphur dew point temperature at the HRSG exit which was a safe condition for the HRSG.

The parameters of the HRSG were investigated as the steam inlet pressure to be 10 bar at 280^0C, steam mass flow rate to be 0.2428 kg/s, and estimates maximum power output as 96.04 kW. But based on the steam turbine manufactures data (Technopa make- 50-200kW) compared with the mass flow rate of the steam, the possible output from the micro steam turbine was 93.63 kW. Furthermore, the flue gas exit temperature from the HRSG in this condition was 154 ^{0}C, which is on the safe side for the HRSG. This represents the simulation trial no 4 mentioned in table 10.

Hence, it was investigated that 93.63 kW energy could be harnessed by the waste heat recovery from the oily sludge incineration, based on the sludge generating data and the incinerator parameters of UJPS.

Furthermore, the ashes collected from the oily sludge incineration could be used for extracting the metal constituents. Based on the previous data extracted from researches based on the metal extracting from the fly ash of the oily sludge, feasibility is there to extract the Vanadium metal from the ashes generated from the incineration. The estimated yearly economic value could be gain will be nearly US$ 19,877.4 which will be LKR nearly 3.7 million (considered the Exchange rate of 1.USD to Rs. 188 LKR). This would be a profitable solution for CEB.

Hence, with the assumption of 26 weeks running pattern for a year of the incinerator, the payback period for the above project will be 2.70 years which is a feasible project. Per year 282.288 MWh of energy could be harnessed via sludge incineration based on the incinerator operation data based on UJPS.

5.0 CONCLUSION

In this study, the waste heat recovery option was considered based on the sludge treatment method used in thermal power stations. There are three thermal power stations driven by heavy fuel oil which belong to the CEB. Among them, two power stations are using incinerators to eliminate generated sludge. That was Uthuru Janani Power Station and the Sapugaskanda Power Station- Plant B. For the study, all the sludge generating data, sludge thermophysical properties, and the running pattern of the incinerator were collected from Uthuru Janani Power Station.

This work investigated the possibility of using the sludge as a fuel for power generation, hot water generation, and waste heat recovery from the oily sludge incineration. The economical method was the waste heat recovery from the incineration since micropower generation could be achieved using the waste heat recovery. Feasibility is there for extracting the metal constituents from the ashes of the incinerated sludge which will be added economic advantage while eliminating the ashes.

As the conclusion of the study, it is valuable that a system presented here to be implemented in the application of oily sludge incineration as a “waste to energy option” for the thermal powers stations while eliminating the generated oily sludge in an environmentally friendly manner rather than selling the sludge at a low cost.

5.1 Key findings

The main key finding of the theses was the feasibility of power generation by incineration of waste sludge, which will be a long-term economical project for CEB.

5.2 Limitations

It is needed to consider the practical limitations such as sulfur dew point at HRSG exit.

Sludge generation depends on the engines running pattern. Engine running pattern depends upon the System Control of Ceylon Electricity Board with the merit order list compared the unit cost of the power station. This was a limitation for the generation of sludge.

Water content in the sludge needs to be minimized in the sludge. If the water content is high combustion of the sludge won't occur. Hence it was required to minimize the water content in the sludge.

5.2 Future work

Investigating the feasibility of waste to energy power generation by incineration of waste sludge from all three Power Stations. Since three numbers of engine operated power stations are available in CEB - Generation division if generated sludge from all three power stations could collect and there will be the feasibility of use as a fuel for generating of electricity by the waste heat of the incinerating the generated sludge from all three power stations while eliminating the generated sludge which was a burden for the CEB.

Suitable Vanadium extraction method for the ashes of the incinerated sludge should be investigated. This will be a solid economic solution for the removed incinerated ashes.

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Appendices

Appendix: A – Data collection on sludge generation

As for the engine manufactures recommendation, the properties of the fuel used in the Uthuru Janani Power Station are as follows

Type of fuel - heavy fuel oil

Table 13:Fuel characteristics [79]

Characteristic	Unit	Value	Test method reference
Kinematic viscosity	Cst at 100°C	55	ISO 3104
	Cst at 50°C	700	
	Redwood No.1 sec.at 100°F	7200	
Density	Kg/m3 at 15°C	991	ISO 3675 or 12185
Water	% V/V	0.5	ISO 3733
Flashpoint, min.	°C	60	ISO 2719
Pour point	°C	30	ISO 3016
Total sediment potential	% m/m	0.1	ISO 10307-2
Sodium	Mg/kg	50	ISO 10478
Al + Si	Mg/kg	31 - 80	ISO 10478 or IP 501 or 470
Sulphur	% m/m	1.51 - 4.50	ISO 8754 or 14596
Ash	% m/m	0.06 - 0.15	ISO 6245
Vanadium	Mg/kg	101 - 600	ISO 14597 or IP 501 or 470
Asphaltenes	% m/m	8.1 - 14.0	ASTM D 3279

Sludge generating data was collected daily basis by the variation of the sludge tank and analysing the incinerated sludge data. The relevant data tabulation is as follows.

Table 14 -Sludge generation at UJPS

Year	**Month**	**Quantity (m^3)**	**Year**	**Month**	**Quantity (m^3)**
2018	January	9.573	2019	January	5.662
	February	12.137		February	13.896
	March	6.695		March	11.858
	April	14.054		April	7.18
	May	12.59		May	14.956
	June	11.473		June	11.289
	July	8.043		July	2.66
	August	9.394		August	3.23
	September	13.087		September	11.507
	October	7.321		October	7.631
	November	7.458		November	7.755
	December	8.71		December	3.423

The graph for the above variation is as follows

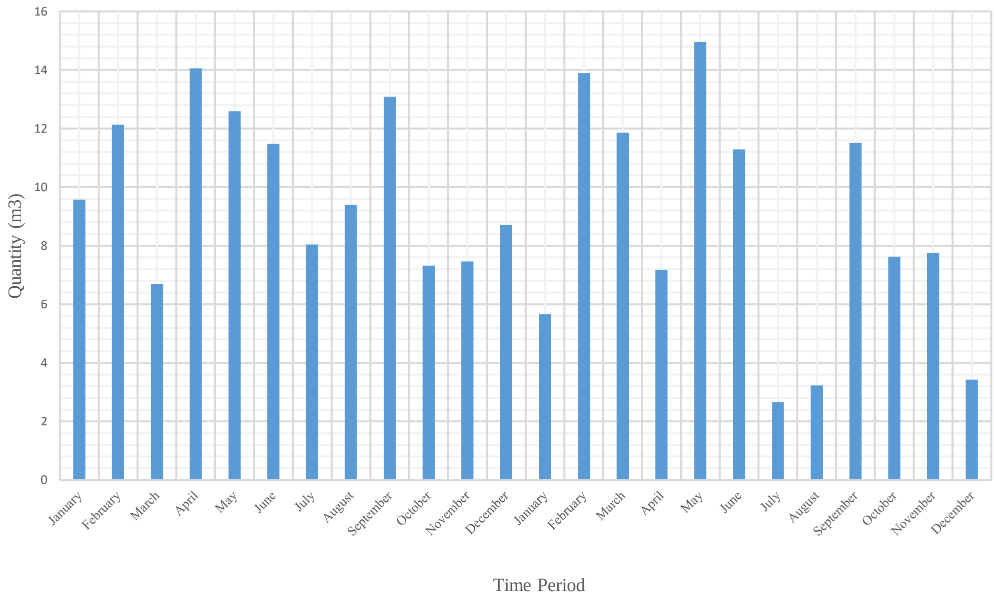


Figure 14 -Variation of the sludge generation for two years

Below mention tabulation represents the energy generated within the period of 2018 January to December 2019.

Table 15:Energy generated at UJPS

Year	Month	MWh	Year	Month	MWh
2018	January	9635.2	2019	January	14359.42
	February	4970.23		February	11633.46
	March	3558.31		March	12083.68
	April	6984.26		April	10413.92
	May	6069.33		May	11599.18
	June	2194.71		June	5310.26
	July	8784.96		July	9577.98
	August	5879.42		August	8400.86
	September	8220.9		September	4988.03
	October	3838.82		October	3150.97
	November	2543		November	6231.84
	December	10929.02		December	6499.85

The graph for the above variation is as follows,

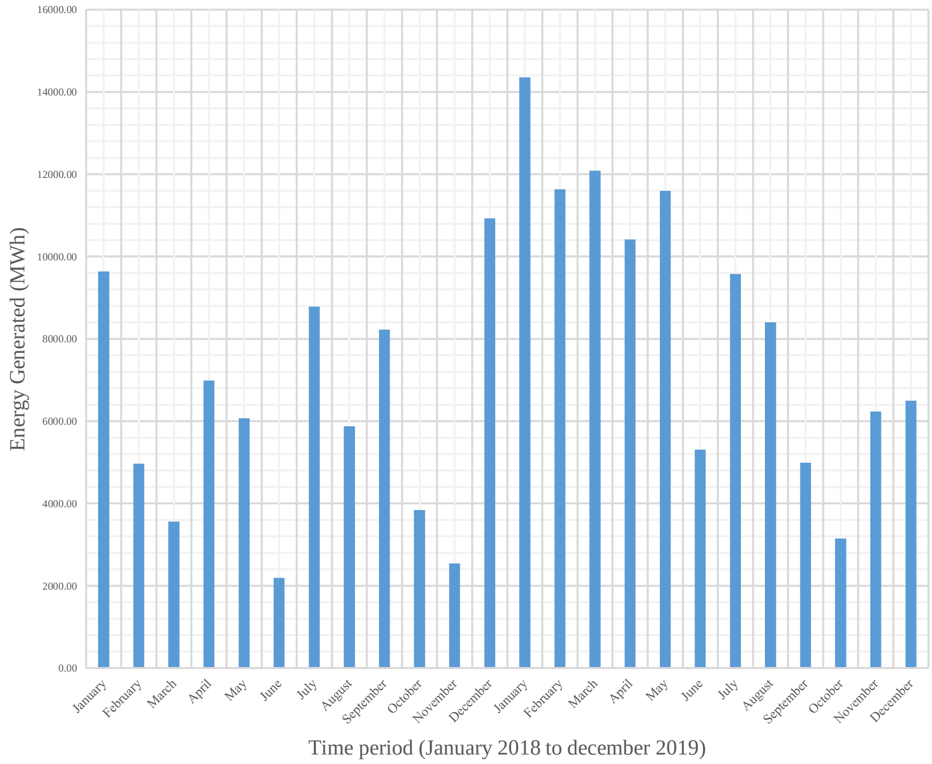


Figure 15- Variation of Energy generation for two years

Below mention tabulation represents the incinerated sludge and lube oil quantity within the period of 2018 January to December 2019.

Table 16:Incinerated sludge and lube oil volume

Year	**Month**	**Incinerated quantity of**		**Year**	**Month**	**Incinerated quantity of**	
		Sludge (m^3)	**Lube oil (m^3)**			**Sludge (m^3)**	**Lube oil (m^3)**
2018	January	18.71	0	2019	January	8.033	3.355
	February	10.816	3.25		February	5.622	0
	March	8.808	3.25		March	4.005	2.565
	April	4.47	0		April	8.584	0
	May	11.696	0.88		May	10.49	2.986
	June	4.527	7.317		June	5.745	4.27
	July	0	6.968		July	6.153	1.24
	August	6.791	0.96		August	7.264	0
	September	8.687	0		September	9.412	1.695
	October	4.181	0		October	4.531	3.687
	November	3.985	0.87		November	5.858	0
	December	1.533	0		December	6.805	0.837

The graph for the above variation is as follows,

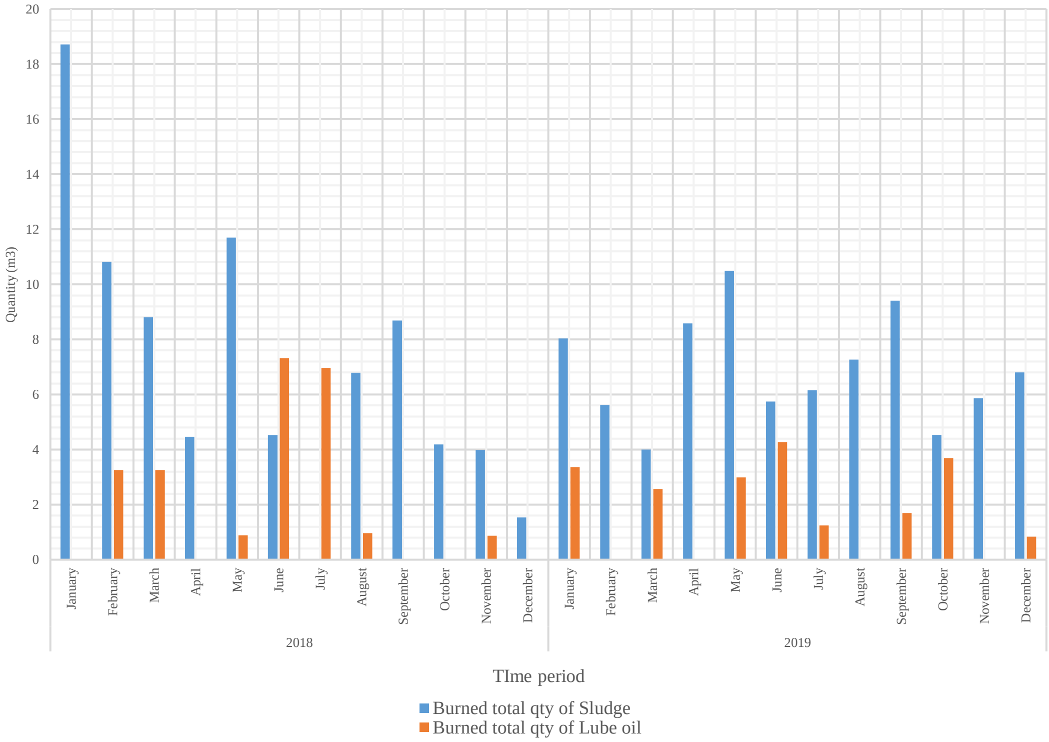


Figure 16 - Incinerated Sludge and Lube oil quantity

Below mention tabulation represents the variation of metal contaminants in the received Heavy Fuel Oil within the period of 2018 January to December 2019.

Table 17-Variation of metal contaminants in the received Heavy Fuel Oil

Year	**Month**	**Metal analysis (mg/kg)**				**Year**	**Month**	**Metal analysis (mg/kg)**			
		Na	**V**	**Al**	**Si**			**Na**	**V**	**Al**	**Si**
2018	January	6	13	6	8	2019	January	3	10	2	1
	February	3	17	2	3		February	4	1	5	10
	March	17	43	19	1		March	5	12	7	5
	April	3	21	2	2		April	5	14	6	4
	May	5	12	7	4		May	11	50	9	7
	June	4	10	3	1		June	13	6	0	0
	July	4	14	7	5		July	4	28	4	5
	August	6	13	6	7		August	0	0	0	0
	September	1	10	7	3		September	4	28	4	5
	October	16	46	19	2		October	26	91	16	12
	November	3	14	9	9		November	20	12	18	9
	December	5	39	10	8		December	1	8	3	4

The graph for the above variation is as follows,

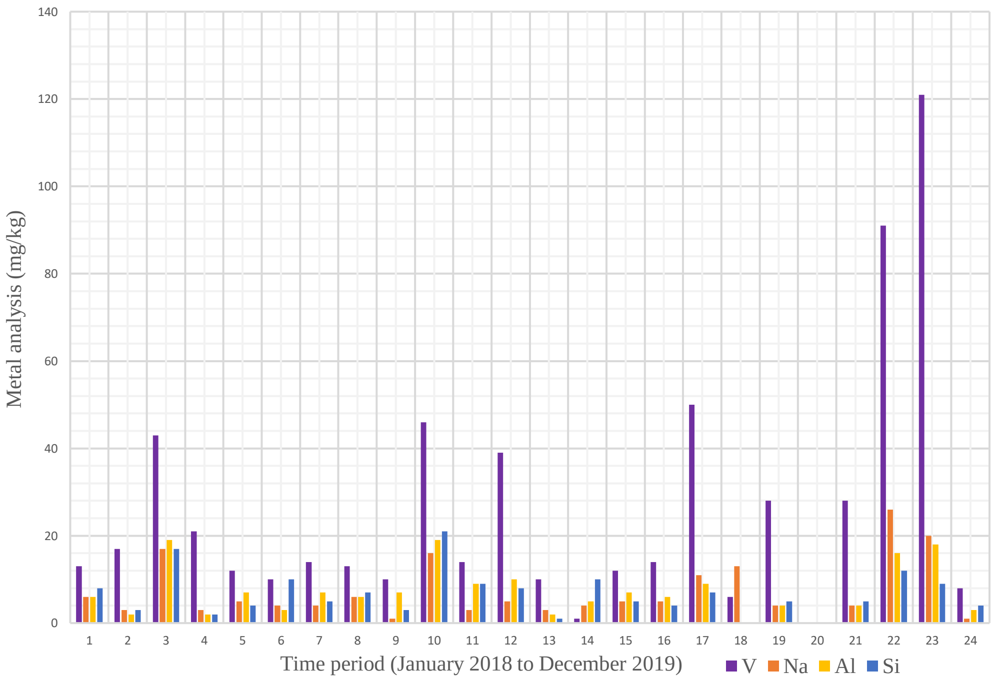


Figure 17- Variation of metal contaminants in received heavy fuel oil

Table 18:Sold sludge quantity data at Sapugaskanda Power station – plant A

Year	**Month**	**Sold sludge quantity (m3)**
2019	May	52.8
	June	79.2
	July	66
	August	52.8
	September	66
	October	66
	November	52.8
	December	52.8
2020	January	92.4
	February	66
	March	105.6

Variation of the generation sludge quantity at Sapugaskanda power station

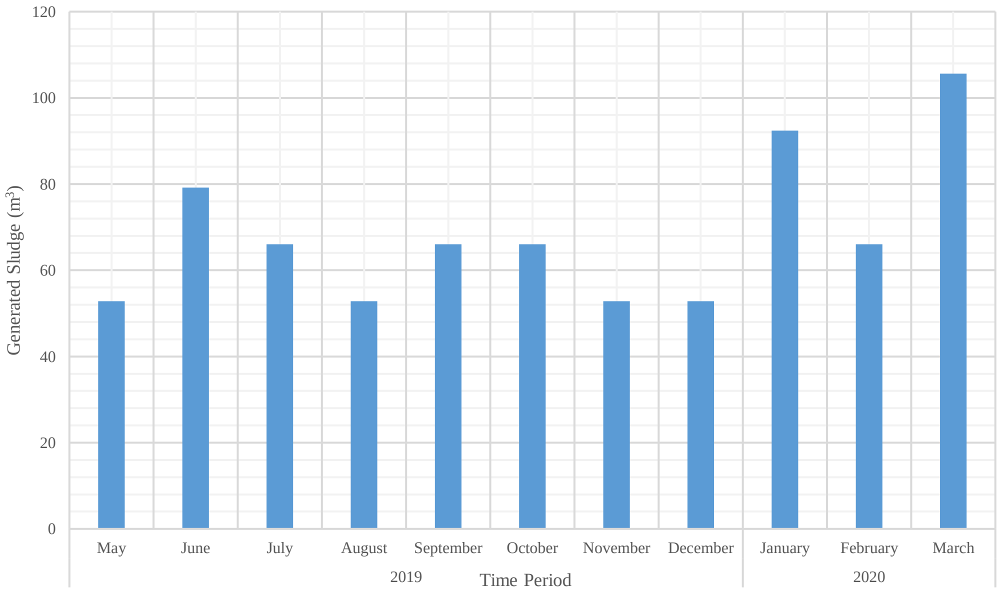


Figure 18:Sold sludge quantity data at Sapugaskanda Power station – plant A

Table 19:Price for one liter of sludge at Sapugaskanda Power Station

Period	Price of one liter of sludge	Total price including tax
2012	Rs.40.88 + VAT 12 %	Rs. 45.78
2013	Rs.45.36 + VAT 12 %	Rs. 50.80
2014	Rs.51.50 + VAT 12 %	Rs.57.60
2015	Rs.36.50 + VAT 11 %	Rs. 40.51
2016	Rs.30.27 + VAT 11%	Rs. 33.59
2017	Rs. 11.00 + VAT 15%	Rs. 12.65
2018	Rs. 14.00 + VAT 15%	Rs. 16.10
2019	Rs. 6.10 + VAT 8%	Rs. 7.015

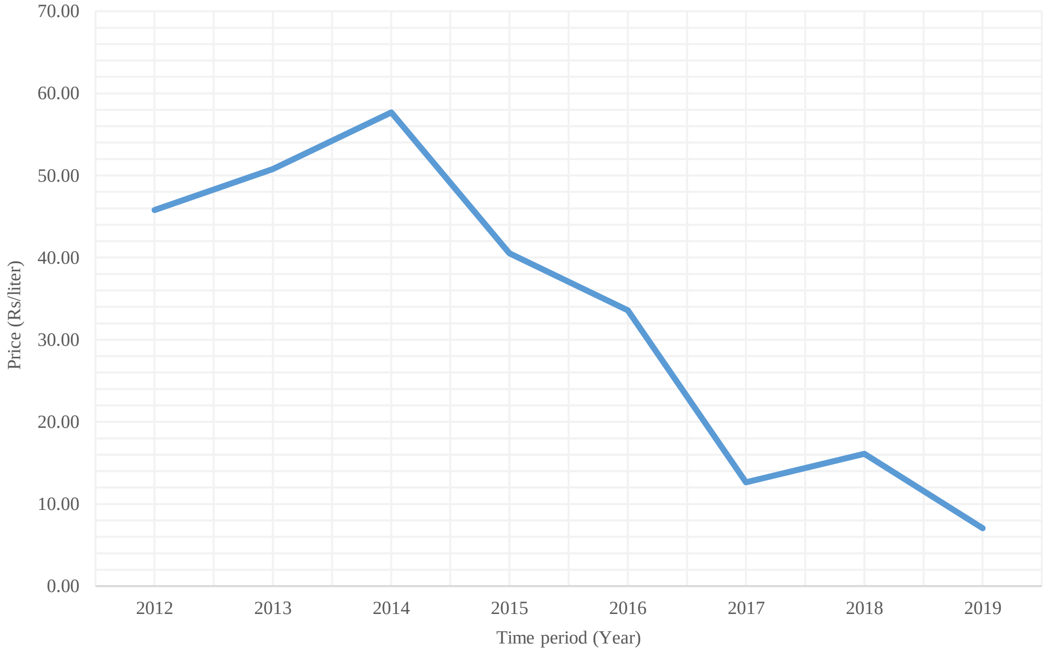


Figure 19:Variation of the sludge price at plant A- Sapugaskanda Power Station

Table 20:Revenue earned for sludge selling

Year	**Month**	**Sold sludge quantity (Liter)**	**Revenue earned from sludge selling**
2019	May	52800	370,392.00
	June	79200	555,588.00
	July	66000	462,990.00
	August	52800	370,392.00
	September	66000	462,990.00
	October	66000	462,990.00
	November	52800	370,392.00
	December	52800	370,392.00
2020	January	92400	648,186.00
	February	66000	462,990.00
	March	105600	740,784.00
Total revenue from sludge selling			5,278,086.00

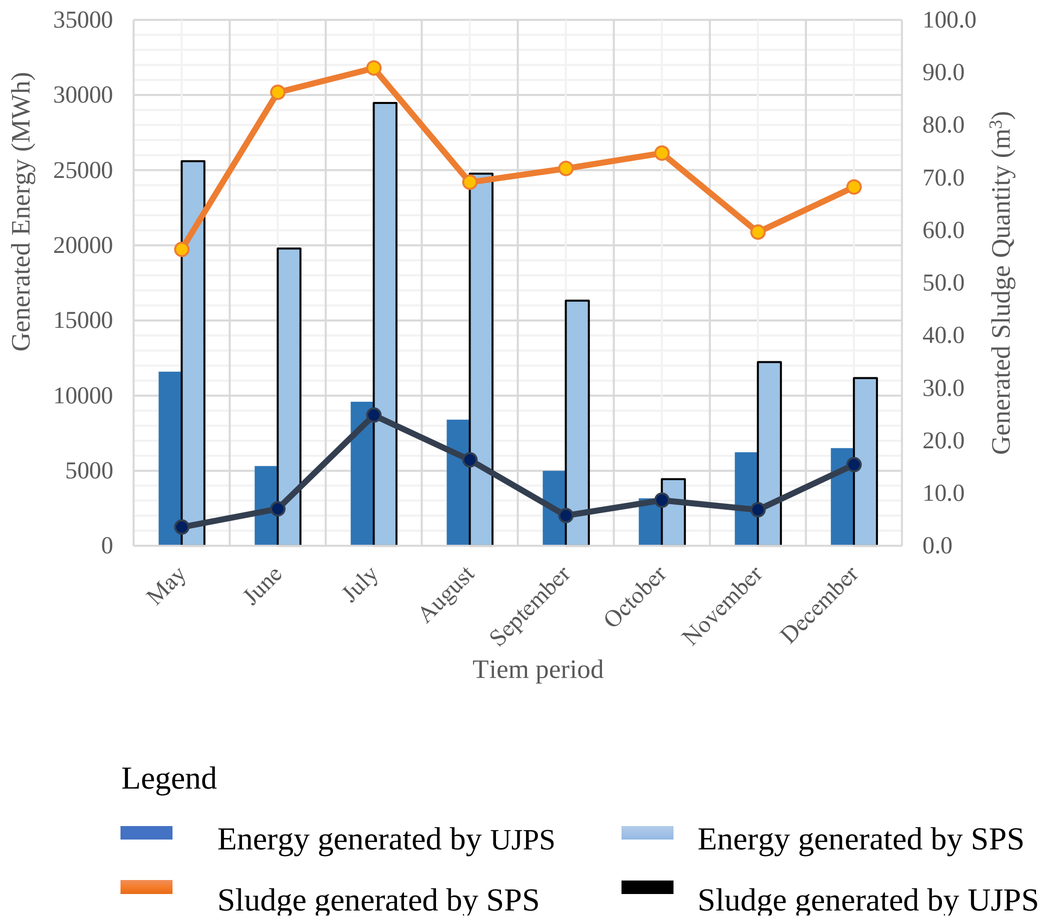


Figure 20:Energy and sludge generation data at UJPS and SPS.

Table 21-Energy and sludge generation data at UJPS and SPS

Year	Month	UJPS		SPS	
		Generated energy MWh	**Sludge generation (m^3)**	**Generated energy MWh**	**Sludge generation (m^3)**
2019	May	11,599.18	3.5	25,590	52.8
	June	5310.26	7.0	19,796	79.2
	July	9577.98	24.8	29,478	66
	August	8400.86	16.3	24,774	52.8
	September	4988.03	5.7	16,321	66
	October	3150.97	8.6	4438	66
	November	6231.84	6.8	12,228	52.8
	December	6499.85	15.4	11,168	52.8
Total		55,758.97	88.3	143,793	488.4

Appendix: B - Sludge Testing- Laboratory Report

CEYLON PETROLEUM STORAGE TERMINALS LIMITED

Oil Installation - Kolonnawa

Tel : 2572307 / 2691643
2694482 / 2532122

LABORATORY REPORT

PARTICULARS OF SAMPLE

Lab Report No.	: CR/2020/089
* Grade of Product	: Oily Sludge
* Sample Type	: Separated from HFO Purification before injection to the Engines.
TA Sample Reference No.	: TA/2020/109
Date Sample Received	: 23/04/2020
Date of Analysis	: 24/04/2020 – 25/04/2020
Our Ref. No.	: CS/2020/084 (Revised Quotation)
Client	: S. P. M. Charithananda, No.65/21, Nisala Mawatha, Webadagalla, Nittambuwa
Method of Analysis	: ASTM & IP Test Methods for Examination of Petroleum Products.

This report relates only to the sample(s) tested and does not guarantee the bulk of the material to be of equal quality

	PROPERTY	TEST METHOD	UNIT	RESULT
1	Calorific Value (Gross)	ASTM D 240 - 17	Kcal/kg	5066
2	**Metal Contaminants**			
	Iron (Fe)	IP 501/05	ppm	117
	Vanadium (V)	IP 501/05		12
	Aluminium (Al)	IP 501/05		244
	Silicon (Si)	IP 501/05		182
	Calcium (Ca)	IP 501/05		368
	Phosphorus (P)	IP 501/05		8
	Zinc (Zn)	IP 501/05		18

* As per the Label of the sample container submitted by Mr. S. P. M. Charithananda.

For MANAGER - LABORATORY
MAIN LABORATORY
CPSTL
Tel./ Fax. : +9411 2572287
E mail : lab@cpstl.lk

Date: 02/05/2020

DEPUTY MANAGER
MAIN LABORATORY
CEYLON PETROLEUM STORAGE TERMINALS LIMITED
KOLONNAWA,
SRI LANKA.

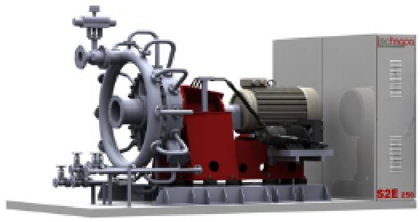
Page 1 of 1

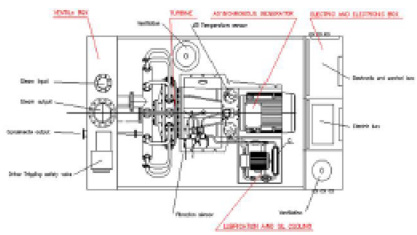
Figure 21:Sample report obtained from CPSTL

Appendix: C - Datasheet - steam turbine

The technical datasheet for the "Technopa" – Micro steam turbines

S2E I. 50-200 kW - Technopa





- Full power reaction time in 10 minutes

Technical parameters

Characteristics	Specification
Electric Power 50-500 kWe	50 – 200 kWe
Incoming steam temperature	min 130 °C max 350 °C
Incoming pressure	min 4,0 bar Abs. max 35,0 bar Abs.
Outcoming steam temperature	min 105 °C max 315 °C
Outcoming steam pressure	min 1,1 bar Abs. max 6,0 bar Abs.
Steam flow	min 1,1-3 t/hour max 20 t/hour

If you have other parameters , please contact TECHNOPA technical service

Electric parameters

Characteristics	Specification
Voltage 50-500 kWe	230V 480VAC /400VAC
Frequency	50 Hz / 60 Hz
Grid-isolated regulation / steady state /	+/- 0,50 % nominal voltage max +/- 0,50 % nominal frequency
Isolation class	IP 55, IP 42

S2E System – No Gear Box – Low Service Costs

Complete Installation Service SupportIncluded

Patented turbine
Non-blade turbine wheel
Slow working revolutions of the turbine/ 3000 rpm /
Efficient alteration of the Velocity Head on the power in turbine is min 95%
Turbine is not a pressure tank

Applications
Reduction turbine / electric energy production
Electric energy production in the prime or secondary steam line

High end level of the components
LANDIS&GYR valves
Armatures made by TYCO company

Focus on the Safety and Reliability
Sensors made by Baluff
Tripping safety valve TYCO

Simple operation and control
Automatic computerized control system
touch panel for operation

Internet connection /optional/

Generator
Asynchronous generator

Certification
Steam and condensate connection based on DIN 2576
CE certification of the S2E module

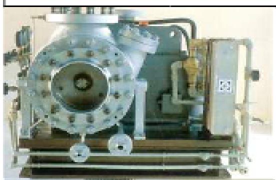
Figure 22 :Technical data sheet of the micro steam turbine-01

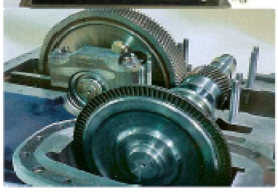
Electric Power	700 – 3000 kWe
Incoming steam temperature	min 130 °C max 380 °C
Incoming steam pressure	min 6,0 bar Abs. max 40,0 bar Abs.
Outcoming steam temperature	min 105 °C max 280 °C
Outcoming steam pressure	min 0,5 bar Abs. max 14 bar Abs.
Steam flow	min 10 t/hour max 30 t/hour

If you have other parameters , please contact TECHNOPA technical service

Electric parameters

Characteristics	Specification
Voltage	230V 480VAC /400VAC
Frequency	50 Hz / 60 Hz
Grid-isolated regulation / steady state /	+/- 0,50 % nominal voltage max +/- 0,50 % nominal frequency
Isolation class	IP 55





Minimum Clearence Requirements

Dimension	Size
Vertical	2000 mm
Horizontal front, and rear side	2000 mm
Horizontal left OR right side	2000 mm

Patented turbine

Blade turbine wheel in one solid piece
Designed for isoentropic drop min 120 kJ / kg
Possibility to control partial steam admission
Turbine is not a pressure tank

Applications

Reduction turbine / electric energy production
Electric energy production in the prime or secondary steam line
Prime mover – ask tech. department

High end level of the components

Special and safe control valve
Special and safe mechanical seal

Focus on the Safety and Reliability

Sensors for safe start/stop and operation control
Servis Control Tripping safety valve TYCO

Simple operation and control

Automatic computerized control system
touch panel for operation
Internet connection /optional/

Generator

Asynchronous Siemens generator

Certification

Steam and condensate connection based on DIN 2576
CE certification of the S2E module

Figure 23:Technical data sheet of the micro steam turbine -02

Appendix: D - EES program codes

(I) Power generation – sludge fired steam boiler

t_f= 350 [C] " flue gas temperature" ; {P_st= 200 [kW] }" power of steam turbine" ; P_max = 35 [bar] " max steam temperatue" ;

t_smax= 350 [C] " max temperature of steam" ; P_out = 6 [bar] " steam ou pressure from st " ;

t_sout= 105 [C] " out temperature of steam";

m_st = m_dotst / 3600; c_p = 2.2[kJ/kg] ; eta_b= 0.8 " boiler efficiency" ;

Cal_f =21205.26 [kJ/kg]" calorific value of fuel" ; rho_f = 960.0 [kg/m3] ; O = 24 ; eta_st = 0.93

t_s = T_SAT (Steam,P=P_max *(convert(bar,kPa))) { pressure of 35 bar} " t_s , saturation temperature for the mentioned pressure"

h_f1= Enthalpy(water,x=1, p=P_max * (convert(bar,kPa)))

H_st= h_f1+ c_p * (t_smax-t_s) " total heat of 1kg of super heated steam"

E_f = (Cal_f * eta_b) / H_st " Energy produce by 1kg of sludge"

M_f = m_dotst / E_f " mass of the fuel required"

V_f = M_f / rho_f " Volume of fuel required to generate 20000kg of steam"

V_day = V_f * O " Volume of fuel required to generate 20000kg of steam per day"

h_out= Enthalpy(water,x=0, p=P_out * (convert(bar,kPa)))

h_go = Enthalpy(water,x=1, p=P_out * (convert(bar,kPa)))

h_fgo = h_go - h_out

s_1 = Entropy(water,x=1,p=P_max * (convert(bar,kPa)))

s_1=s_2 " isentropic efficiency"

s_fo3 = Entropy(water,x=0,p=P_out * (convert(bar,kPa)))

s_fgo =Entropy(water,x=1,p=P_out * (convert(bar,kPa)))

s_fg = s_fgo - s_fo3

X = (s_2- s_fo3)/ s_fg

h_2 = h_out + X * h_fgo

P_st = m_st * (h_f1- h_2) *eta_st

(II) The sludge requirement for a minimum mass flow rate of the steam required to run the steam turbine.

t_f= 350 [C] " flue gas temperature" ; {P_st= 200 [kW] }" power of steam turbine" ; {P_max = 35 [bar]} " max

steam temperatue" ; t_smax= 350 [C] " max temperature of steam" ; P_out = 1.1 [bar] " steam ou pressure from st " ;

t_sout= 105 [C] " out temperature odf steam";

{m_dotst = 20000 [kg/h]} " required steam flow rate"

m_st = m_dotst /3600

; c_p = 2.2 [kJ/kg] ; eta_b= 0.8 " boiler efficiency" ;

Cal_f = 21196.14[kJ/kg]" calorific value of fuel" ; rho_f = 960.0 [kg/m3] ; O = 24 ; eta_st = 0.93

t_s = T_SAT (Steam,P=P_max *(convert(bar,kPa))) { pressure of 35 bar} " t_s , saturation temoerature for the

mentioned pressure"

h_f1= Enthalpy(water,x=1, p=P_max * (convert(bar,kPa)))

H_st= h_f1+ c_p * (t_smax-t_s) " total heat of 1kg of super heated steam"

E_f = (Cal_f * eta_b) / H_st " Energy produce by 1kg of sludge"

M_f = m_dotst / E_f " mass of the fuel required"

V_f = M_f / rho_f " Volume of fuel required to generate 20000kg of steam"

V_day = V_f * O " Volume of fuel required to generate 20000kg of steam per day"

h_out= Enthalpy(water,x=0, p=P_out * (convert(bar,kPa)))

h_go = Enthalpy(water,x=1, p=P_out * (convert(bar,kPa)))

h_fgo = h_go - h_out

s_1 = Entropy(water,x=1,p=P_max * (convert(bar,kPa)))

s_1=s_2 " isentropic effiency"

s_fo3 = Entropy(water,x=0,p=P_out * (convert(bar,kPa)))

s_fgo =Entropy(water,x=1,p=P_out * (convert(bar,kPa)))

s_fg = s_fgo - s_fo3

X = (s_2- s_fo3)/ s_fg

(III) Hot water generation using sludge

Calculation for the fesibility analysis of Hot water system

P_w = 4 [bar] ; t_1= 27[C] " water temperature" ; t_2 = 100[C] ; t_3= 140 [C]" water required temperature" ; C =4.2 [kJ/kg]

eta_o = 0.68 ; m = 1 [kg] " mass of water" ; Cal_f = 21205.26 [kJ/kg]" calorific value of fuel" ; rho_f = 960.0 [kg/m3] ; O = 24 [H]

D = 30 ;

{S_d = 9.23 [m3]} " maximum generation of sludge per month"

S_h = ((S_d * rho_f) / (D * O)) " maximum sludge generation of sludge per hour"

h_f1= Enthalpy (water,x=0, p=P_w * (convert(bar,kPa)))

t_s = T_SAT (Steam,P=P_w * (convert(bar,kPa))) { pressure of4 bar} " t_s , saturation temperature for the mentioned pressure"

E_1 = m * C *(t_2 - t_1)

E_2= h_f1+ C* (t_3-t_2)

E = E_1 +E_2

M_h = (S_h * Cal_f * eta_o) / E

Appendix:E - Acid dew point of flue gas

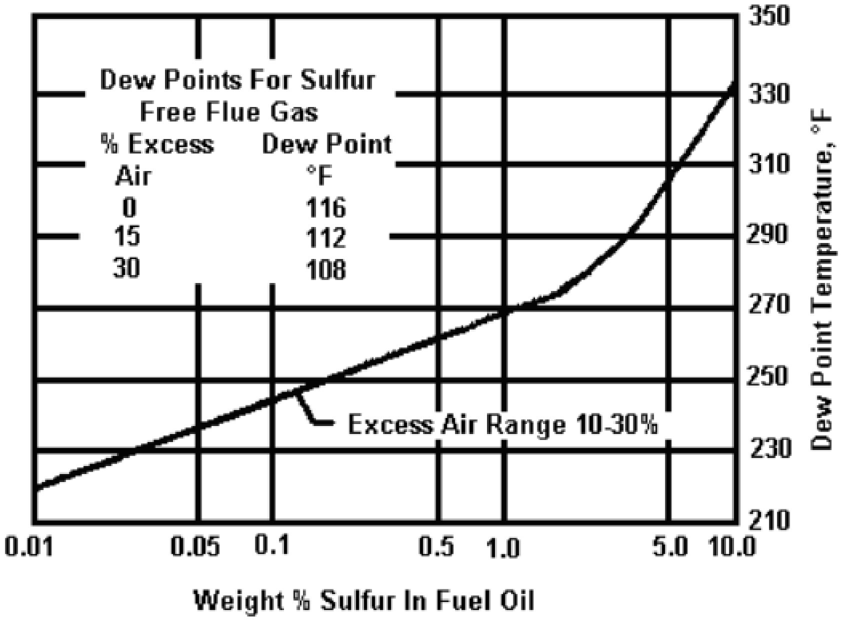


Figure 24 - Acid Dew Point of Flue Gas [80]

Appendix: F: Average exhaust gas temperature

Currently, the generating sludge at UJPS is burning via the incinerator. An image of the main panel of the incinerator unit is as in figure no-32.

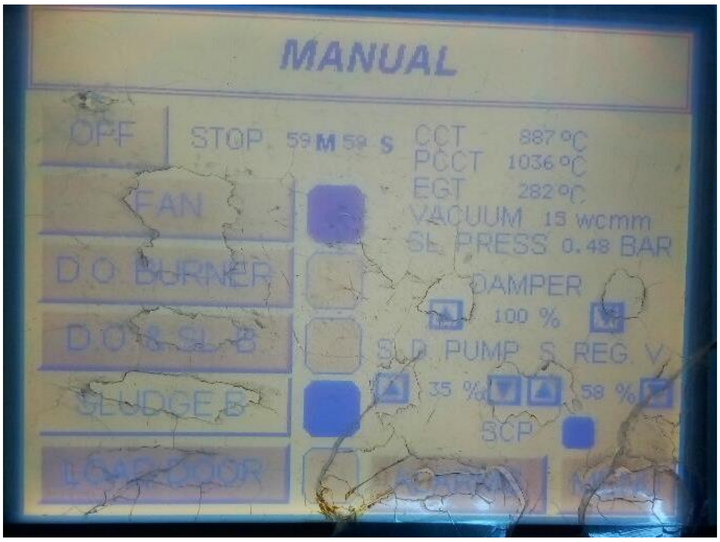


Figure 25- Indication panel of the incinerator (Original in colour)

Exhaust gas temperature at sludge burning time was monitored for five days of operation of the incinerator with one-hour intervals. A graph was plotted to get the average exhaust gas temperature of the unit since it is varying from 2 ^{0}C -5 ^{0}C. The average exhaust gas temperature was found as 282^{0}C.

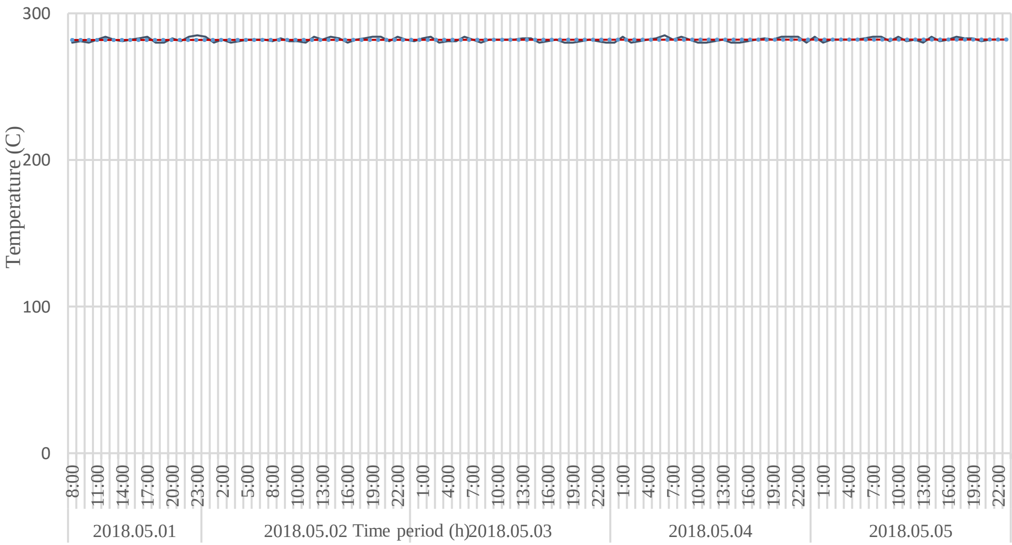


Figure 26- Variation of the exhaust gas temperature

(I) The waste heat recovery potential of flue gas

Fuel mass flow rate = 150l/h

m_f $= \frac{150 \text{ x } 960}{1000}$ Kg/h = 144.0 kg/h

= 0.040 kg/s

The mass flow rate of the exhaust gas $= 12{,}800 \frac{\text{Nm3}}{\text{H}}$

Density of the flue gas $= 1.35 \frac{\text{Kg}}{\text{Nm3}}$

Mass flow rate of flue gas m_g $= 12{,}800 \frac{\text{Nm3}}{\text{H}} \text{ X } 1.35 \frac{\text{Kg}}{\text{Nm3}}$ =17,280 kg/h

= 4.8 kg/s

Appendix G: Modeling a suitable HRSG

(I) Modeling a suitable HRSG for the incinerator

Variation of turbine output power

p_sh = 16 [bar] ; c_p=1.05[kJ/kg.K]; { P_tur=90[kW]} ; t_sh=280 [C] ; p_out = 1.1[bar] ; eta_is =.93; eta_m =0.98 ;

m_dot_gas=5.625[kg/s] ; t_g1= 282 [C] ; hl=2 " %" ; C = 4.18 [kJ/kg.C]

{ Selected pinch point temperature difference, t_ppdif is}

{t_ppdif =8 [C]}

t_ppdif =t_g3-t_s

t_apprdif = 8[C]

t_appr = t_s - t_apprdif

t_s = T_SAT (Steam,P=p_sh * (convert(bar,kPa))) { pressure of 16 bar}

h_s1 = Enthalpy(water,x=0,P=p_sh*(convert(bar,kPa)))

h_s2 = Enthalpy(steam,x=1,P=p_sh*(convert(bar,kPa)))

" the value of t_g3 can be determine by applying heat balance over the evaporator and the superheater by means of

super heat and evaporation data on the steam side"

m_dot_gas*c_p*(t_g1 - t_g3) = m_dot_st*(h_sh - h_appr) "------(1)"

{in the above equation t_g3 or m_dot_st value both are unknown. But to get the value of t_g3 it is required to find the value for

steam mass flow rate. This value can be find by applying the heat balance over the turbine}

P_tur = m_dot_st * (h_sh - h_out) * eta_m "------(2)"

s=ENTROPY(Steam, T=t_sh,P=p_sh*(convert(bar,kPa)))

h_outis = ENTHALPY(Steam,S=s,P=p_out*(convert(bar,kPa)))

{ Enthalpy of superted steam can found in steam or H-S chart at 16 bar , 280 C or in steam}

h_sh = ENTHALPY(Steam,T=t_sh,P=p_sh* (convert(bar,kPa)))

{ Enthalpy out from turbine can found in h-s diagram, by first finding the isentropic out let enthalpy, hence real out let enthalpy can be

calculated}

h_out = h_sh - eta_is*(h_sh -h_outis) "--------(3)"

{If heat balance applied to span over the entire steam cycle, stack temperature could be calculated}

m_dot_gas * c_p * (t_g1 - t_g4) * ((100-hl)/100) = m_dot_st * (h_sh - h_fw)

{ Assuming that the specific heat is same tg1 to t_g3 as tg1 to t_g4}

h_fw = ENTHALPY (water,x=0,P=p_out *(convert(bar,kPa)))

{h_appr = ENTHALPY (Water,T=t_appr,P=p_sh*(convert(bar,kPa)))}

h_appr = C * t_appr

m_dot_gas *c_p*(t_g2 -t_g3) = m_dot_st*(h_s2-h_appr)

(II) Variation of steam pressure while keeping the pinch point temperature at 8^0C.

{p_sh = 16 [bar]} ; c_p=1.05[kJ/kg.K]; t_sh=280 [C] ; p_out = 1.1[bar] ; eta_is =.93; eta_m =0.98 ;

m_dot_gas=5.625[kg/s] ; t_g1= 282 [C] ; hl=2 " %" ; C = 4.18 [kJ/kg.C]

{ Selected pinch point temperature difference, t_ppdif is}

{t_ppdif =8 [C]}

t_ppdif =t_g3-t_s

{t_apprdif = 8[C]}

t_appr = t_s - 8

t_s = T_SAT (Steam,P=p_sh * (convert(bar,kPa))) { pressure of 16 bar}

h_s1 = Enthalpy(water,x=0,P=p_sh*(convert(bar,kPa)))

h_s2 = Enthalpy(steam,x=1,P=p_sh*(convert(bar,kPa)))

" the value of t_g3 can be determine by applying heat balance over the evaporator and the superheater by means of

super heat and evaporation data on the steam side"

m_dot_gas*c_p*(t_g1 - t_g3) = m_dot_st*(h_sh - h_appr) "------(1)"

{in the above equation t_g3 or m_dot_st value both are unknown. But to get the value of t_g3 it is required to find the value for

steam mass flow rate. This value can be find by applying the heat balance over the turbine}

P_tur = m_dot_st * (h_sh - h_out) * eta_m "------(2)"

s=ENTROPY(Steam, T=t_sh,P=p_sh*(convert(bar,kPa)))

h_outis = ENTHALPY(Steam,S=s,P=p_out*(convert(bar,kPa)))

{ Enthalpy of super-heated steam can find in steam or H-S chart at 17 bar , 280 C or in steam}

h_sh = ENTHALPY(Steam, T=t_sh,P=p_sh* (convert(bar,kPa)))

{ Enthalpy out from turbine can found in h-s diagram, by first finding the isentropic out let enthalpy, hence real out let enthalpy can be calculated}

h_out = h_sh - eta_is*(h_sh -h_outis) "--------(3)"

{If heat balance applied to span over the entire steam cycle, stack temperature could be calculated}

m_dot_gas * c_p * (t_g1 - t_g4) * ((100-hl)/100) = m_dot_st * (h_sh - h_fw)

{ Assuming that the specific heat is same tg1 to t_g3 as tg1 to t_g4}

h_fw = ENTHALPY (water,x=0,P=p_out *(convert(bar,kPa)))

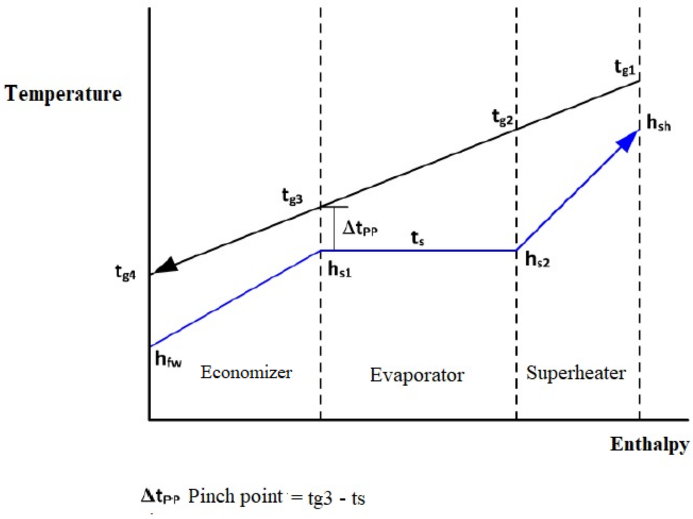
{h_appr = ENTHALPY (Water,T=t_appr,P=p_sh*(convert(bar,kPa)))}

h_appr = C * t_appr

{heat balance for the evaporator}

m_dot_gas *c_p*(t_g2 -t_g3) = m_dot_st*(h_s2-h_appr)

(III) Calculation



Temperature profiles for a single-pressure HRSG

Figure 9-Typical temperature profiles for a single-pressure HRSG

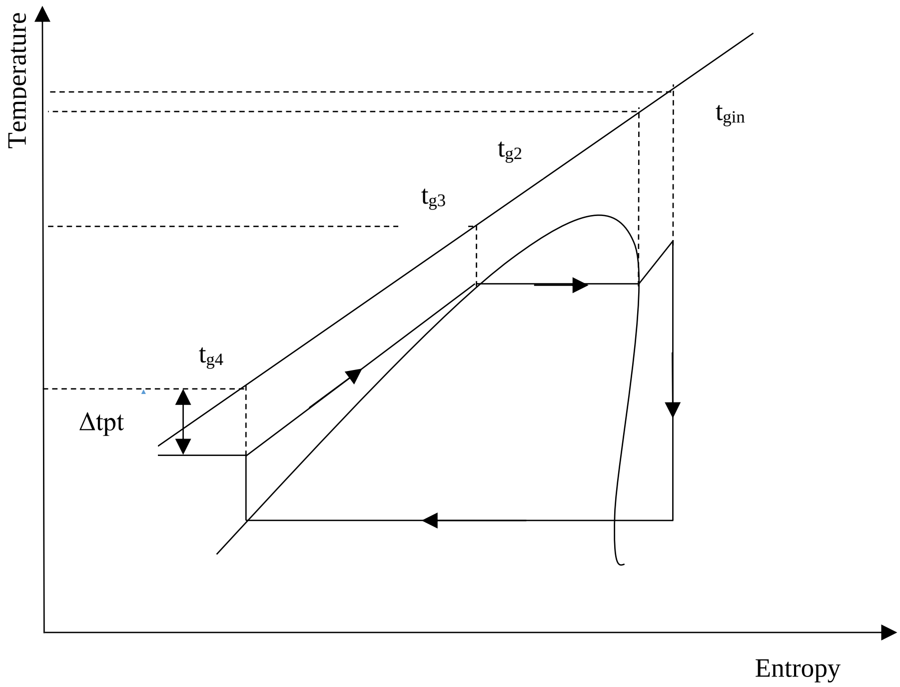


Figure 27 – Rankine cycle [77]

Following parameters were assumed for the calculation

Inlet parameter of the steam was taken as 16 bar and 280^{o}C

The pressure in the condenser (p_{out}) = 1.1 bar

Steam turbine power output (P_{stm}) = 90 kW (Appendix B)

Isentropic efficiency of the steam turbine (η_{stm}) = 0.93

Mechanical efficiency of the steam turbine (η_{me}) = 0.98

HRSG, approach temperature ($\Delta tppt$) = 8^{0}C

Value of heat losses (h_{l0}) from the HRSG to surrounding = 0.02 [75]

Following calculation process was carried out to make the parameters to optimum level while not affecting the plant operation. Keeping these conditions satisfactorily the possible stream turbine output in kW and the temperature difference for pinch point was taken in Celsius.

Pinch point temperature difference = $\Delta tppt$ = 8^{0}C

From the equation (6),

$$\Delta t_{pt} = t_{g3} - t_s$$

Where, t_s = 201.37 ^{0}C at 16 bar saturation temperature.

From equation (10); energy balance applies to: t_{g1} and t_{g3};

$$m_{St} (h_{shs} - h_{apr}) = m_{gs} . C_p . (t_{g1}-t_{g3})$$

$$m_{st} = \frac{M_{gs} \text{ X } C_p \text{ x } (t_{g1}-t_{g3})}{(h_{shs} - h_{apr})}$$

The variables in the above equation no (10), $t_{g3,}$ and m_{st} both are unknown. To evaluate the value of t_{g3} the value of m_{st} should be known. Hence, to find the value of m_{st} heat balance can be applied for the steam turbine.

From equation no (11); applying heat balance to the turbine,

$$m_{St} . (h_{Shs}-h_{ou}). h_{me} = P_{stm}$$

$$m_{st} = \frac{P_{stm}}{(h_{shs} - h_{ou}) \times \eta_{me}}$$

From equation no (12), isentropic outlet enthalpy,

$$h_{ou} = h_{shs} - h_{stm}(h_{shs} - h_{ouis})$$

$$h_{stm} = \frac{h_{shs} - h_{ou}}{(h_{shs} - h_{ouis})}$$

Finding the h_{ouis} value in equation (12),

$S_{hs} = S_{out} = 6.8059$ (Isentropic) - at 16 bar -280 ^{0}C temperature, entropy values.

$S_{out} = S_f + x. S_{fg}$ ($S_f = 1.3330$ kJ/kgk, at 1.1 bar and $S_{fg} = 5.9938$ kJ/kg k)

Hence, $x = 0.9130$

$H_{outis} = h_f + x. H_{fg}$ (hf = 428.84 kJ/kg , at 1.1 bar and $h_{fg} = 2250.3$ kJ/kg)

Hnece, $h_{outis} = 2,483.36$ kJ/kg.

$H_{shs} = 2990.10$ kJ/kg (at 16 bar -280 ^{0}C temperature - enthalpy value)

From the equation no. (11),

Steam mass flow rate (m_{st}) $= \dfrac{P_{stm}}{(h_{shs} - h_{ou}) \times \eta_{me}}$

$$= \frac{90}{(2990.10 - 2518.83) \times 0.98}$$

$$= 0.194 \text{ kg/s}$$

From equation (13),

$$h_{apr} = C_p \ (t_s - t_{pt})$$

$$= 4.187\ (204.3-8) \qquad = 821.9 \text{ kJ/kg.}$$

From equation (10),

$$t_{g3} = t_{g1} - \left[\frac{m_{st}\ (h_{shs} - h_{apr})}{m_{gs} \text{ x } C_p} \right] = 210.38\ ^0C$$

From the equation (6),

The pinch point temperature difference $= \Delta_{tpt}$

$$\Delta tpt = t_{g3} - ts$$

$$= 210.38\ ^0C - 201.37\ ^0C = 9.01\ ^0C$$

From the equation (14); applying heat balance to span over the whole steam cycle,

$$m_{Gs} .C_p .(t_{g1} - t_{g4})(1 - h_{Lo}) = m_{St} . (h_{Shs} - h_{Sw})$$

$$t_{g1} - t_{g4} = \frac{m_{st} \text{ x } (h_{shs} - h_{sw})}{m_{gs} \text{ x } C_p \text{ x } (1 - h_{lo})}$$

Assuming that the specific heat is not changing from t_{g1} to t_{g4}.

Enthalpy of feed water was investigated after the condenser, saturated water at 1.1 bar. Neglected the liquid water enthalpy across the pump hence feed water enthalpy value at 16 bar pressure was the enthalpy after the condenser (saturated water)

Hence,

h_{shs} = enthalpy value (super-heated steam at 16 bar and 280 ^0C)= 2990.10 kJ/kg

h_{sw} = enthalpy of saturated water at 1.1 bar = 428.84 kJ/kg

From equation (14),

$$t_{g4} = t_{g1} - \left[\frac{m_{st}\ (h_{shs} - h_{sw})}{m_{gs} \text{ x } C_p \text{ x } (1 - h_{lo})} \right]$$

$$= 196.16\ ^0C$$

From the equation (15); applying heat balance to economizer,

$$m_{gs} C_p (t_{g3} - t_{g4}) = m_{st}(h_{apr} - h_{sw})$$

$$t_{g3} - t_{g4} = \frac{m_{st} \times (h_{apr} - h_{sw})}{m_{gs} \times C_p}$$

From the equation (16); heat balance over the evaporator,

$$m_{gs} C_p (t_{g2} - t_{g3}) = m_{st} (h_{s2} - h_{apr})$$

$$t_{g2} - t_{g3} = \frac{m_{st} \ (h_{s2} - h_{apr})}{m_{gs} \times C_p}$$

From equation (13), $h_{apr} = C_p \ (t_s - t_{pt})$

$$h_{apr} = 4.187 \times (201.37 - 8)$$

$$= 809.64 \text{ kJ/kg}$$

From equation (16), $t_{g2} = t_{g3} + [\frac{M_{st} \ (h_{s2} - h_{apr})}{m_{gs} \times C_p}]$

$$= 277.14 \ ^{\circ}C$$

When optimizing, the pinch point temperature should fall between 8^0C to 16^0C. If the obtained pinch point temperature results get closer to 8^0C the power output from the HRSG will be maximum.

Finding h_{out} ;

Finding the h_{outis} value,

$S_{hs} = S_{out} = 6.8059$ (Isentropic) at 16 bar -280 ^{0}C temperature , entropy values.

$S_{out} = S_f + x \, . \, S_{fg}$ (S_f = 1.3330 kJ/kgk, at 1.1 bar and S_{fg} = 5.9938 kJ/kgk)

X = 0.9130

$H_{outis} = h_f + x. \ H_{fg}$ (h_f = 428.84 kJ/kg , at 1.1 bar and h_{fg} = 2250.3 kJ/kg)

= 2,483.36 kJ/kg.

H_{shs} = 2990.10 kJ/kg at 16 bar -280 ^{0}C temperature , enthalpy value

From equation (7),

$H_{ou} = h_{shs} - \eta stm \ (h_{shs} - h_{outis})$

$= 2990.10 – 0.93 \times (2990.10-2483.36)$

$= 2518.83$ kJ/kg

$$T_{g4} = t_{g1} – \left[\frac{M_{st}\ (h_{shs} – h_{sw})}{M_{gs} \times c_p \times (1-h_{lo})} \right]$$

$$= 282 – \left[\frac{0.194\ (2990.10– 428.84)}{5.625 \times 1.05 \times (1-0.02)}\right]$$

$$= 282- 85.84$$

$$= 196.16\ ^0C$$

From the equation (12),

The enthalpy at approach point temperature can be find by below mentioned equation.

$$H_{apr} = C_p\ (t_s-t_{app})$$

$$H_{apr} = 4.187\ (201.37- 8) = 809.64 \text{ kJ/kg}$$

(IV) EES codes for the sludge requirement for the steam turbine operation

{p_sh = 16 [bar]} ; c_p=1.05[kJ/kg.K]; t_sh=280 [C] ; p_out = 1.1[bar] ; eta_is =.93; eta_m =0.98 ;

m_dot_gas=5.625[kg/s] ; t_g1= 282 [C] ; hl=2 " %" ; C = 4.18 [kJ/kg.C]

{ Selected pinch point temperature difference, t_ppdif is}

{t_ppdif =8 [C]}

t_ppdif =t_g3-t_s

{t_apprdif = 8[C]}

t_appr = t_s - 8

t_s = T_SAT (Steam,P=p_sh * (convert(bar,kPa))) { pressure of 16 bar}

h_s1 = Enthalpy(water,x=0,P=p_sh*(convert(bar,kPa)))

h_s2 = Enthalpy(steam,x=1,P=p_sh*(convert(bar,kPa)))

" the value of t_g3 can be determine by applying heat balance over the evaporator and the superheater by means of

super heat and evaporation data on the steam side"

m_dot_gas*c_p*(t_g1 - t_g3) = m_dot_st*(h_sh - h_appr) "------(1)"

{in the above equation t_g3 or m_dot_st value both are unknown. But to get the value of t_g3 it is required to find the value for

steam mass flow rate. This value can be find by applying the heat balance over the turbine}

P_tur = m_dot_st * (h_sh - h_out) * eta_m "------(2)"

s=ENTROPY(Steam, T=t_sh,P=p_sh*(convert(bar,kPa)))

h_outis = ENTHALPY(Steam,S=s,P=p_out*(convert(bar,kPa)))

{ Enthalpy of superted steam can found in steam or H-S chart at 16 bar , 280 C or in steam}

h_sh = ENTHALPY(Steam,T=t_sh,P=p_sh* (convert(bar,kPa)))

{ Enthalpy out from turbine can found in h-s diagram, by first finding the isentropic out let enthalpy,hence real out let enthalpy can be

calculated}

h_out = h_sh - eta_is*(h_sh -h_outis) "--------(3)"

{If heat balance applied to span over the entire steam cycle, stack temperature could be calculated}

m_dot_gas * c_p * (t_g1 - t_g4) * ((100-hl)/100) = m_dot_st * (h_sh - h_fw)

{ Assuming that the specific heat is same tg1 to t_g3 as tg1 to t_g4}

h_fw = ENTHALPY (water,x=0,P=p_out *(convert(bar,kPa)))

{h_appr = ENTHALPY (Water,T=t_appr,P=p_sh*(convert(bar,kPa)))}

h_appr = C * t_appr

{heat balance for the evaporator}

m_dot_gas *c_p*(t_g2 -t_g3) = m_dot_st*(h_s2-h_appr)

P_st = P_tur

; c_p1 = 1.8 [kJ/kg] ; eta_b= 0.55 " boiler efficiency" ;

Cal_f = 21196.14[kJ/kg]" calorific value of fuel" ; rho_f = 960.0 [kg/m3] ; O = 24 ; eta_st = 0.93

h_f1= Enthalpy (Steam,x=1,P=p_sh*(convert(bar,kPa)))

H_st= h_f1+ c_p1 * (t_g1-t_s) " total heat of 1kg of super heated steam"

Q_e = H_st * m_dot_st*3600 " energy required for the steam"

M_f = Q_e/ (Cal_f * eta_b) " mass of the fuel required"

V_f = M_f / rho_f " Volume of fuel required to generate kg of steam"

V_day = V_f * O " Volume of fuel required to generate kg of steam for a day"

Appendix: H- Payback period for HRSG

Cost calculation/payback period for proposed HRSG with Steam Turbine

For the above project budgetary coasting is as follows

Table 22-Budgetary cost

No	Description	The cost involved (LKR)
1	Steam turbine	2,000,000.00
2	Heat recovery steam generator	2,500,000.00
3	Steam piping for the HRSG	1,000,000.00
4	Water treatment plant	1,300,000.00
5	Pumps (Ex. Feed water pumps /condensate extraction)	1,500,000.00
6	Civil Works	1,300,000.00
7	Additional Auxiliaries	1,000,000.00
8	Electrical & instrumentation cost	2,000,000.00
9	Direct cost	1,500,000.00
10	Indirect Cost	1,200,000.00
11	Contingencies -5%	765,000.00
Total Cost		16,065,000.00

Following data considered to prepare the estimated project costing.

For the steam turbine following things are attached in the cost for the turnkey installation.

- Turbine, gearbox,
- Control valve,
- Electric and Control box and system,
- Operation software,
- Protector switchgear and generator fuse
- Installation Supervising
- Internal cabling (Module - Control box connection)
- Including the freight charges

For the Heat Recovery Steam Generator

- Included the installation & freight charges
- Required piping for the HRSG cost separately
- Since the demineralized water required for the steam turbine, the existing water treatment plant cannot be used.
- Separate pumps required as “duty-standby” condition for the HRSG & the steam system

Small civil construction works will be required for the structure for the HRSG and the Stack. The existing stack could be used before the diverter damper for the isolation of the HRSG if maintenance works are required.

The direct cost will include the followings

- Procurement, fabrication, and installation of bulk materials.
- Site preparations (earthworks).
- Procurement, fabrication, and associated services

The indirect cost will include the followings,

- Temporary construction facilities including worker lodgings/services, secure lay-down areas, warehouses, etc.
- Temporary construction services.
- Construction equipment.
- Freight.
- Vendor representatives.
- Capital spares.
- Commissioning Spares.
- First Fills.
- Engineering, procurement, and construction management services (including travel expenses).
- Third-party engineering

The following Owner's costs are not included in the cost estimate

- Client facility in EPCM contractor's office.
- Additional costs due to adverse weather conditions.
- Fuel costs during construction.
- Mobile equipment.
- Test laboratories and office furniture.
- Freight charges to site.
- Currency hedging.
- Additional project insurances depending on site-specific risks.
- All taxes, duties, levies, fees, and royalties
- Development fees and approval costs of Statutory Authorities
- Environmental monitoring.
- Escalation beyond the base date of the estimate.
- Variations to foreign currency exchange rates.
- Project closure plan and site cleanup and rehabilitation.
- Schedule delays and associated costs, such as those caused by:

- Unexpected site conditions
- Unidentified ground conditions
- Labor disputes
- Force majeure, and
- Unforeseen Permit applications.
- Escalation beyond the base date of the estimate

The calculation for the payback period

The steam turbine could be operated only when the incinerator is running. The incinerator operation depends upon the sludge generation in the power station. Sludge generation proportionate to the full load operation of the power station. Because the power station is running continuously more sludge will generate from the fuel separators and other activities. Hence the incinerator needs to run continuously.

Considering the collected data for the two years of the operation of the incinerator at UJPS for one month the normal operation of the incinerator is ten days. Five days continuously for two weeks. For one year of period nearly 26 weeks.

To generate steam, it will take more time in the initial stage of operation of the Incinerator. To avoid this delay time can use the existing 7 bar steam condensate line to heat the feed water tank of the HRSG with some modification for the existing steam circuit. Budget form additional auxiliaries could use for this modification. Hence the feed water tank temperature can be kept in 80-100^{0}C. With this modification can assume that HRSG will generate steam with a delay of 4 hours of starting the incinerator.

As for the above assumptions, for one-week continuous operation,

Steam turbine operating hours for one week	= (24-4) + 4x 24 = 116 hours
Generating power of the micro steam turbine	= 93.63 kW
Total generate power per one week	= 93.63 x 116 kWh
	= 10,861.08 kWh

As for the CEB rates 1kWh [81] = Rs. 16.63

But actual IPP selling price for CEB needs to consider for the calculation. Hence considered as Rs.21.00 as selling price for CEB

Generated cost = Rs. 21.00 x 10,861.08

= Rs. 228,082.68

Cash flow per annum = 26 x 180,619.76

= Rs. 5,930,149.68

Payback period for the above project $= \frac{\text{Initial Investment}}{\text{Net cash flow}}$

$= \frac{16{,}065{,}000.00}{5{,}930{,}149.68}$

= 2.70 Years

Since the bay back period of 2.70 years, the above project is feasible.