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Modelling, Retrofitting and Thermoeconomic Assessment of Lillesjoverket Waste to Heat Power Plant

Master's thesis in Sustainable Energy Systems Programme

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CHALMERS UNIVERSITY OF TECHNOLOGY
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Abstract

Every year more than 99% of household wastes is recycled in Sweden (Freden, 2017). Only in 2016 over 2.3 million tonnes of household wastes was converted into the form of energy in waste power plants. Not only Swedish power plants combust the household wastes collected from their area, but also import them from other countries like Norway or Ireland. (Avfall Sverige, 2017)

Nowadays around 50% of waste is combusted due to energy recovery. On the Swedish area there are 32 waste to heat power plants which significantly increased the amount of energy produced from this type of fuel in last 40 years. (Freden, 2017)

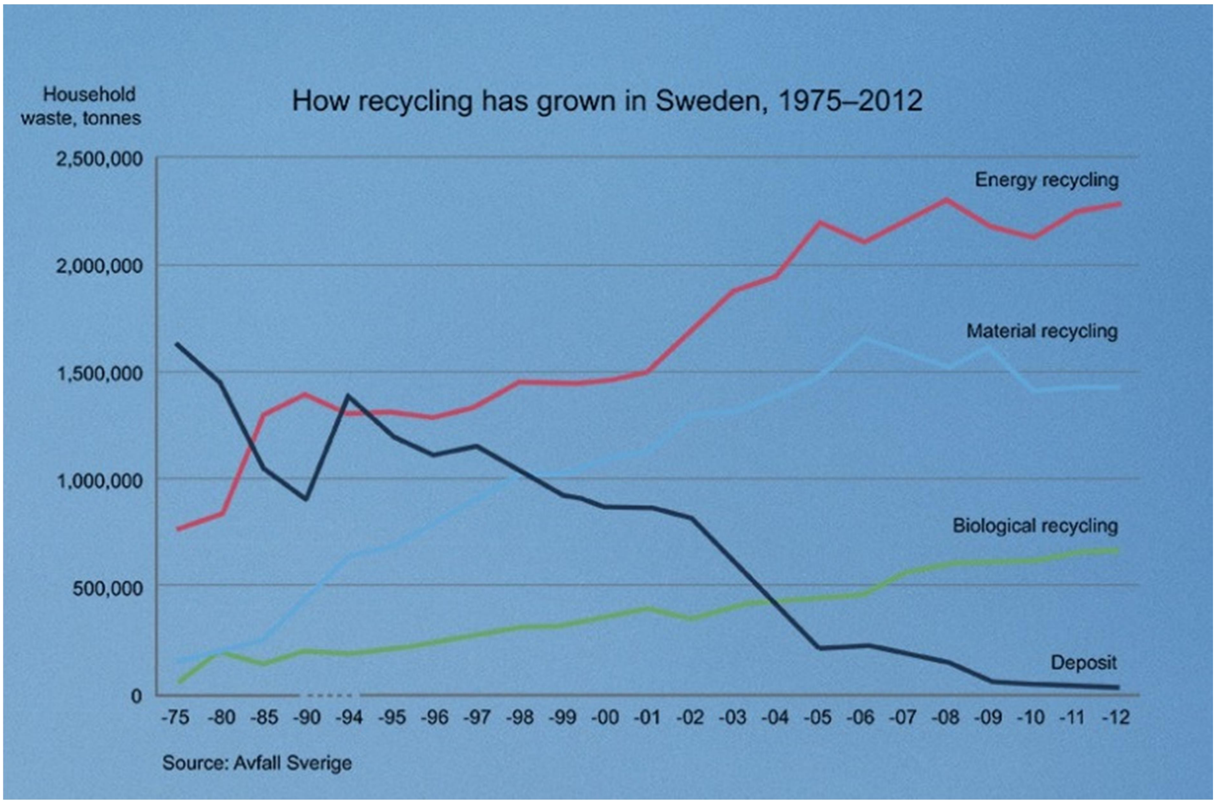

Figure 1 Methods of waste recycling in Sweden (Freden, 2017)

One of the waste to heat power plants in western Sweden is Lillesjoverket power plant. It belongs to Uddevalla Energi AB and every year it produces 200 GWh of heat and 60 GWh of electricity only by combustion of household wastes. (Uddevalla Energi AB, 2017)

By studying schemes and instrumentation and by collecting data through Lillesjoverket power plant control system, possible modelling and retrofitting actions were specified and further analysed. All actions were associated by the thermoeconomic assessment to obtain degree of profitability.

Retrofitting scenarios prepared for given subsystems in the power plant allowed to decrease usage of steam and thereby increase the efficiency of production of heat and electricity in the main cycle.

Analysis of the flue gas cleaning system leads to decreasing amount of hazardous particles and thereby the environmental impact on the surrounding area.

One of the targets of the thesis was to create the equipment cost database for equipment types typically found in a waste-to-energy plants. By using economy factors and indexes like e.g. CEPCI – costing actions can be compared through the previous decades and present economy trends on the equipment market.

In this thesis two retrofitting scenarios were presented focusing on the gas cleaning systems of the plant and their downstream impact on heat exchanger fouling. First scenario describes influence of electrostatic precipitator cross-section inlet on flue gas velocity and residence time inside the system. The second retrofitting scenario assumes installation of dust removing equipment for cleaning primary air used in combustion. Both of scenarios allow to save steam which can be redirected to the production process and in consequence increase the yearly income and total efficiency of the power plant. However, the payback period of the required investment in the first scenario is significantly smaller, although the payback period of the required investment in the second case could be reduced by applying more realistic installation factors based on the plant engineers expertise.

Keywords: Retrofitting, Steam savings, Thermoeconomy analysis, Equipment cost database, Waste incineration, Energy efficiency, Flue gas cleaning, Electrostatic precipitators

Acknowledgments

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Also I would like to thank Jadwiga and Piotr Kak – my lovely parents, Joanna and Herbert Krol – my closest friends and Basia Malicka – my wonderful fiancée. Your support, your optimism and motivating me in the difficult times was priceless and hearten me during this project.

I bow my head in front of you all with high hopes that you still will be with me with your advices, support and help.

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1. Introduction

1.1. Background

Lillesjoverket is a waste incineration cogeneration plant where commercial and municipal flammable waste is combusted. At present, all fuels come from the nearest region. Every year around 98000 tonnes of waste is fired in furnace. It corresponds to 200000 MWh of heat – which is 2/3 of total annual heat output. In addition 60000 MWh of electricity is produced. After the combustion there exists residual products like ash, waste water and condensate. The products of combustion are used in various ways. For example after metal separation slug ash is used as a finishing material in Havstrip in Uddevalla. Thanks to Uddevalla seaside location waste water after carefully cleaning and checking is removed to the sea. (Uddevalla Energi AB, 2017)

Lillesjoverket waste-to-heat power plant was started in 2009 and since this time there was no major retrofit process. Thus, the goal of this master thesis project is to indicate possible changes and retrofit scenarios which in future will be useful for improving the thermal plant efficiency and fulfilling emissions limits with acceptable payback period for the required investment..

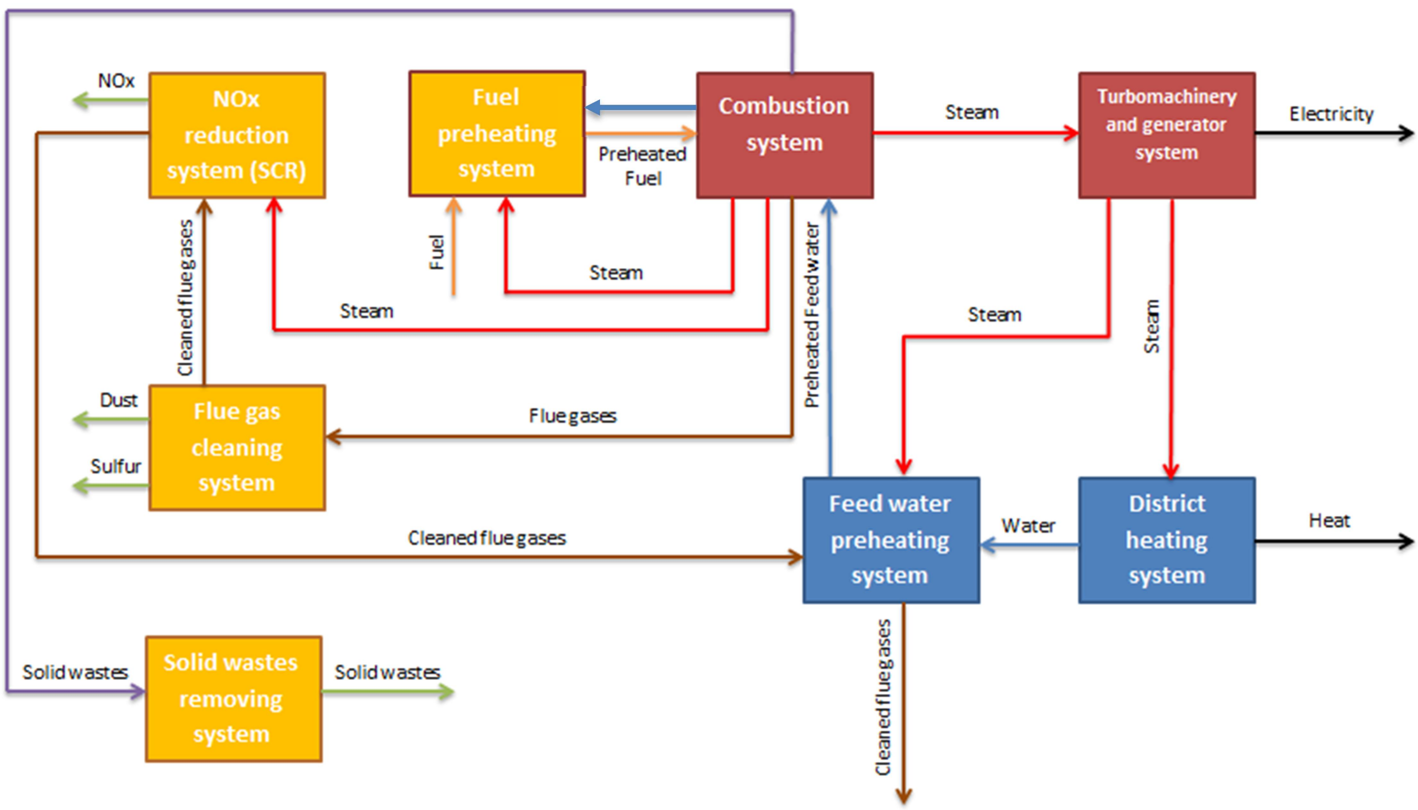


Figure 2 Simplified diagram of systems used in Lillesjoverket

1.2. Aims and objectives

The aim of the master thesis project is to model, retrofit and perform thermoeconomic assessment of Lillesjoverket waste to heat power plant in Uddevalla. After data extraction, every system highlighted in figure 2 were taken into deeper analysis. Together with power plant staff, the trial to discover potential problems was made. After investigating problems in given system, the proposed solution was performed and discussed with production manager. Two major problems were found out and further described in retrofitting scenarios chapter. Every solution led to increase the total efficiency of the plant and increase potential income. However it was not determined that every proposed solution was recommended to implement. If, after economy analysis occurred that the implementation is not reasonable since for example payback period time is too long, the solution was denied. For every proposed scenario, detailed economy analysis was performed.

The whole project is performed for Uddevalla Energi Company.

1.3. Limitations

The retrofitting part is limited to the major components of the power plant. The minor ones like pipes, ducts, valves etc. will not be analysed.

All steps were performed with discussion and consultation with the Uddevalla Energi and Supervisor of this project from Chalmers. The main idea was to choose several major parts of power plant indicated by people in company to further investigation and prepare retrofit scenarios.

The role of company is significant at this stage since that they mainly choose what is most crucial from their point of view.

1.4. Report outline

The report outline is as follows

Chapter 2 presents system of collecting data and how the data can be exported from it

Chapter 3 presents equipment cost database and the relevant calculations involved.

Chapter 4 presents theory of electrostatic precipitators which is necessary to understand retrofitting scenarios 1 and 2

Chapter 5 presents retrofitting scenarios 1 and 2, thermoeconomy assessment and conclusions.

2. Methodology

Following master project was divided for several parts presented in the figure below:

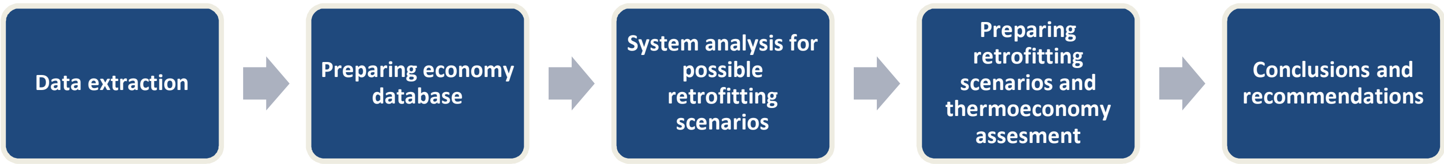


Figure 3 An overview of the project work procedure

After collecting, data was filtered and the gross errors were eliminated to increase the accuracy for further simulations. The exact procedure of data extraction will be presented in chapter 2.1.

The second step was preparing equipment cost database which was later used during predicting the direct equipment cost. By taking into consideration cost curves and equations which were found in literature and the CEPCI index to account for the time dependency of the equipment costs, the purpose was to achieve an acceptable cost accuracy and validated in various ways. The database was divided to equipment families. Every family (heat exchangers, compressors, dust removal systems etc.) was later validated by comparing it with other readily (online) available databases and by comparing with real bills and offers provided by Uddevalla Energi. The process of creating database will be presented in chapter 3.

In the introduction it was mentioned that Lillesjoverket is generally new and modern power plant.. Mainly by discussions with engineer in the power plant two major problems were highlighted. Both of them concerned fouling problems and affects more than one subsystems. After the analysis it occurs that primary air provided into combustion is contaminated by significant amount of dust which causes fouling of the water-gas heat exchanger and in consequence decreases the heat transfer ratio. This decreases the temperature of primary air after heat exchanger and leads to increase the amount of steam in the steam-gas heat exchanger. The second retrofitting scenario was connected with decreasing efficiency of electrostatic precipitator. Decreasing efficiency led to fouling problems on heat exchanger and in consequence to decrease the temperature of flue gases before SCR system what in consequence could lead to situation when chemical reactions cannot be performed due to too low temperature in the reactor. Detailed the description of the scenarios are placed in the chapter 4.

Every retrofitted action was associated by thermoeconomic assessment which indicates if the scenario is reasonable from economic point of view. This was supported by the equipment cost database, literature and experience of supervisors in the power plant to calculate the payback period of the retrofit scenarios.

Based on the results, conclusions are drawn and recommendations for power plant are made.

2.1. Data extraction

In this paragraph the process of data extraction from the power plant server will be described.

First assumption which was made due to extract data from the system was that the time range for this project is one year of continuous work without any unplanned breaks. It means that maintenance break which constitute for 3 weeks in May every year are acceptable. The time range which was selected to further analysis was year 2017. Nothing unplanned happened during that range

During analysis selected sub-systems listed on figure 2 it often happens that it was not necessary to extract data for the whole year, but instead for three months. Example of that is the retrofitting scenario 1, where selected data refers to 3 months of the normal operation of ESP system. However, these 3 months are still contained in the year 2017.

Due to inaccurate measurements, old measurement instruments and other factors which influence on the reliability of measurement, relatively often gross errors and measurement errors occurred. The most typical procedure in this case was to remove any data point which was unrealistic in compare to the trend. To claim which point is and which is not reasonable the rule of thumb was used. If there was any controversy about the measurements, the consultation with the power plant staff was made.

The most usual data collected from the power plant was temperature data, which was the best indicator of the increasing of fouling problem in power plant. After collecting the temperature measurement point for the given time range it was transformed into form of chart where it was easier to determine if any point can be considered as the gross error or not. Additional benefit was that power plant measurement system exactly indicate at which date, hour and minute the point was measured, so it was definitely easier to localise the point in the data table and make further action as removing or keeping it to later analysis.

Additional parameters which also were used in the preparing scenarios for improving the work of power plant were pressure and volumetric flow. What was disadvantage in this project was that there were no amount of dust measured after and before ESP what could influence on the accuracy of further analysis.

If any of using data cannot be collected from the ASPEN PROCESS DATA, it was collected from the technical documentation of the given equipment. Usually it was data like heat load, size or material of which the equipment was made. It is worth to remember that data collecting from the technical documentation is valid for the new equipment and in time parameters like heat load or efficiency are decreased.

If there were any doubts about collecting data, the consultation with the power plant staff was made.

3. Equipment cost database

The main purpose to create equipment cost database was to simplify and accelerate financial evaluation of retrofitting scenarios performed in further stages of project. Initially it was unknown what equipment will need to be considered in retrofit scenarios. Moreover, the database can be used in future retrofit scenarios. That is why the assumption was to prepare the database which at start contains most popular energy equipment and in case of necessity expand it to demanded machines.

The equipment in the database are:

- Heat exchangers
    - Shell and tube
    - Kettle vaporizers
    - Spiral plate
    - Plate and frame
- Electrofilters
    - Rigid electrode, flange to flange
    - Two stage electrostatic precipitators without precooler
    - Two stage electrostatic precipitators with precooler
- Medium and low pressure compressors
    - Reciprocating air compressor
    - Helical screw
    - Straight lobe
- High pressure compressor
    - Reciprocating air compressor
    - Centrifugal compressor
- Boilers
    - Field erected
    - Small package
    - Large package
    - Waste heat
- Turbines
    - Steam turbine
    - Gas turbine
- Generators
    - Turbine drive (including boiler&installation)

3.1. CEPCI Index

The index was introduced in 1963 and from this time is really useful tool during preparing approximated cost of power plant equipment. The cost of equipment varies between the years – it is affected by many different factors like inflation, developing new technologies, access to resources etc. Every three months new CEPCI Index is presented and by calculating the respective CEPCI ratio between the year from which the data comes from and the current year it is possible to estimate the present equipment cost. (Eschenbach, 2011)

Example: If in the 1987 CEPCI Index was equal to 370 and in 2017 was equal to 638, and the electrofilter cost around \$120000 in 1987, it means that approximate cost in 2017 will be as follows (Garett, 1987)

$$Cost(2017) = \frac{CEPCI\ 2017}{CEPCI\ 1987} * Cost(1987)\ (1)$$

3.2. Heat exchangers

Every type of heat exchanger presented in the database has its own unique cost function. However final cost depends not only on the function but on additional parameters as well.

These parameters are:

- Construction material
- Operating pressure
- Tube length and surface

In general cost functions for heat exchangers listed on previous page presents as follows (Silla, 2003):

- **Floating head**

$$Cb = exp\{11.667 - 0.8709[\ln(area)] + 0.09005[\ln(area)^2]\}\ (2)$$

- **Fixed head**

$$Cb = exp\{11.0545 - 0.9228[\ln(area)] + 0.09861[\ln(area)^2]\}\ (3)$$

- **U-tube**

$$Cb = exp\{11.147 - 0.9186[\ln(area)] + 0.09790[\ln(area)^2]\}\ (4)$$

- **Kettle Vaporizer**

$$Cb = exp\{11.967 - 0.8709[\ln(area)] + 0.09005[\ln(area)^2]\}\ (5)$$

- **Spiral plate**

$$Cb = 100 * (area)^{0,59}\ (6)$$

- **Plate and frame**

$$Cb = 100 * (area)^{0,78} (7)$$

The first four heat exchangers presented above are of the shell and tube type. The final cost of them is based not only on the Cb costs but also on three additional factors: material factor, pressure factor, length factor.

3.2.1. Material factor

Material factor can be calculated formulas follows:

$$F_m = a + (\frac{A}{100})^b \ (8)$$

Where ***a*** and ***b*** are proper coefficients and ***A*** is the area of heat exchanger. Coefficients for given type of material are presented in the table below (Peters, 1991):

Table 1. Materials coefficients for shell and tube heat exchangers

Material	Coefficient a	Coefficient b
Carbon Steel/Carbon Steel	0	0
Carbon Steel/Brass	1,08	0,05
Carbon Steel/Stainless Steel	1,75	0,13
Carbon Steel/Monel	2,10	0,13
Carbon Steel/Titanium	5,2	0,16
Carbon Steel/Cr-Mo Steel	1,55	0,05
Cr-Mo Steel/Cr-Mo Steel	1,7	0,07
Stainless Steel/Stainless Steel	2,7	0,07
Monel/Monel	3,3	0,08
Titanium/Titanium	9,6	0,05

. Material influence for plate and frame heat exchangers presents table 2.

Table 2. Material influence factor for spiral, plate and frame heat exchangers

Material factor for Spiral plate and frame	
Carbon steel	1
Mild steel	0,43
Nickel	1,2
Titanium	2,6
Stainless Steel	1,1

3.2.2. Pressure factor

Pressure factor is expressed by following equation:

$$F_P = 0{,}9803 + 0{,}018\left(\frac{P}{100}\right) + 0{,}0017\left(\frac{P}{100}\right)^2 \quad (9)$$

It is important to notice that pressure in this equation should be expressed in *psia* unit. (Garett, 1987)

3.2.3. Tube length correction

Depending on the length of tubes, a correction factor should be included by using following table:

Table 3. Length correction factor for shell-tube heat exchangers

Tube length, F_L [ft]	Correction factor
8	1,25
12	1,12
16	1,05
20	1

3.2.4. Final cost

The final purchasing cost of shell and tube heat exchanger is defined as (Seider, 2010):

$$C_p = C_B F_M F_P F_L \quad (10.1)$$

When the final purchasing cost of plate and frame heat exchanger can be define as (The Tubular Exchanger Manufacturers Organisation):

$$C_p = C_B F_M \quad (10.2)$$

Please take into consideration that this formula and following correction factors are valid only for shell-tube heat exchangers. In case of costing plate and frame heat exchangers – main factor remains the area and material of construction. (Garett, 1987)

3.3. Electrofilters

Similarly to heat exchangers final cost is the sum of purchasing cost of equipment and additional options chosen by user.

Two types of electrofilters were taken into consideration

- Rigid electrode, flange to flange
- Two stage electrostatic precipitator
  - With precooler
  - Without precooler

3.3.1. Rigid electrode, flange to flange

The main cost function parameter is the collection plates area. That is why this type strongly depends on the material of which it is made. Rigid electrode, flange to flange can be supported by additional equipment that in consequence can increase the final cost about 45%.

The cost curve and cost equation is defined as in the figure below:

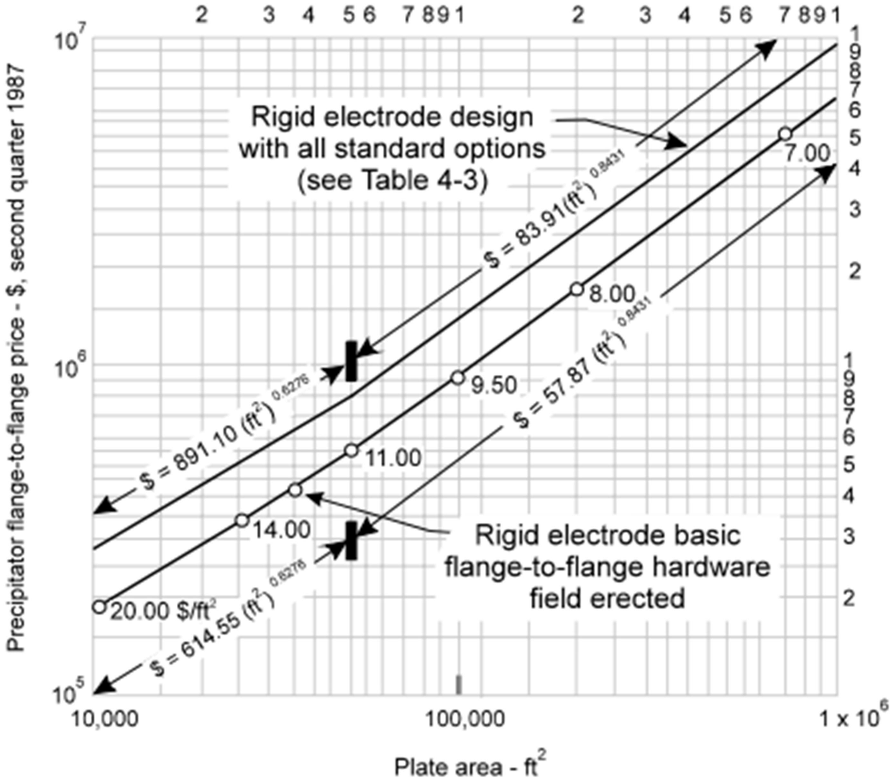


Figure 4. Flange to flange cost curve and cost equation (Turner, 1995)

As it is mentioned on figure 4, there is possibility to estimating final cost for all standard options, possible options are presented below in the table (Turner, 1995).

Table 4 Approximate minimum and maximum cost of standard options in flange to flange ESP system

Additional option	Minimum additional cost as a share of total purchasing cost	Maximum additional cost as a share of total purchasing cost
Inlet and outlet nozzles and diffuser plate	0,08	0,1
Hopper auxiliaries/heaters, level detectors	0,08	0,1
Weather enclosures and stair access	0,08	0,1
Structural supports	0,05	0,05
Insulators	0,08	0,1

Strong influence on the final cost of flange to flange type of electrostatic precipitator has also the material of which the system is made. In the table 5 the most popular material and their coefficient were described (Turner, 1995).

Table 5. List of materials and factors for flange to flange ESP system

Material	Factor
Carbon Steel, 18 gauge	1
Stainless Steel, 304	1,3
Stainless Steel, 316	1,7
Carpenter 20 CB-3	1,9
Monel 400	2,3
Nickel 200	3,2
Titanium	4,5

The cost firstly should be estimated for carbon steel, 18 gauge and then multiplied by proper factor for given material.

Then the final cost is function of initial purchasing cost multiplied by factor indicated by additional options, material and proper CEPCI ratio.

Comment: It would be nice to complement this kind of calculation with an example (perhaps in an Appendix section). In principle this could also be done for heat exchangers., etc.

3.3.2. Two stage electrostatic precipitator

The main factor which differs two stage electrostatic precipitator from flange to flange type is the main parameter which describes the cost function. For this type the main parameter is volumetric flow, for this case it is not so dependent on the material which it is made of and the material has not such a crucial role for increase the work efficiency. There are two possible options of purchasing two stage ESP: with or without precooler. Since for these two options cost curve and equations are different, they were treated separately in the database.

The cost curve and equation are described as follows:

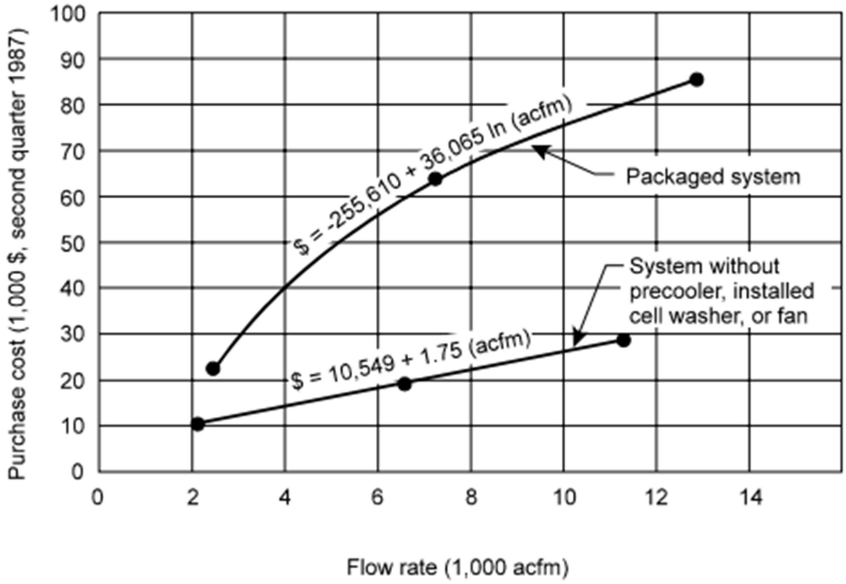


Figure 5. Two stage ESP system cost curve and equation (Mahajani, 2009)

There exists additional options which can be implemented during estimation of the system cost. All of them are presented in the table below: (Theodore, 2008)

Table 6. Additional options for two stage electrostatic precipitator

Table 4-5. Items that increase ESP costs

Item	Factor or Total Cost	Applied to
Rigid-frame electrode with restricted plate height	1.0-1.25	ESP base cost
Type 304 stainless-steel collector plates and precipitator walls	1.3-1.5	ESP base cost
All-stainless construction	2-3	ESP base cost
ESP with drag conveyor hoppers (paper mill)	1.1	ESP base cost
Retrofit installations	1.3-1.5	ESP base cost
Wet ESP		
Sulfuric acid mist	\$65-\$95/ft^2	-
Sulfuric acid mist (special installation)	Up to \$120/ft^2	-
Coke oven off-gas	\$90-\$120/ft^2	-

Source: U.S. EPA 1990.

Two important things need to be considered about table 6. First is that it allows to calculate also wet ESP system – however this system was not implemented into the data base due to too high approximation level. The second thing is that the factor of total cost is estimated for year

1990, what is different than rest data used for ESP systems, it means that also different CEPCI index must be used during evaluation final and valid for 2018 cost.

3.4. Other equipment types

In this sub-chapter other type of equipment will be described. The common factor for all of them is the method how the final cost was evaluated. There was no direct cost equation but instead of it, the curve on log-log scale was presented. To evaluate the most approximate data the following equation was used (Garett, 1987):

$$Cost\ 2 = Cost\ 1 * \left(\frac{Size\ 2}{Size\ 1}\right)^{a} \quad (11)$$

Where:

Cost 2 – target cost which is searched by user

Cost 1 – cost referred to size 1 at the log-log scale

Size 2 – target size for which the cost is estimated

Size 1 – size referred to cost 1 at the log-log scale

a – size exponent

The procedure to estimate the Cost 2 was as follows

1. Find the point at the cost curve which is easy to estimate at the log-log scale
2. Read the Cost 1 and Size 1 for this point
3. Choose the target size (Size 2)
4. Insert proper size exponent which is different for different equipment type
5. Calculate Cost 2

This procedure is similar for all equipment types described in this section and was implemented into the database. All charts and figured referred to following type of costing are presented in the Appendix A2.

3.4.1. Medium and low pressure compressors

For medium and low pressure compressors crucial parameter was volumetric flow rate. Following types were implemented into database

- Reciprocating air compressor with the size exponent equal to: 0,34
- Helical screw with the size exponent equal to: 0,87
- Straight lobe with the size exponent equal to: 0,51

3.4.2. High pressure compressor

For high pressure compressors crucial parameter was power input. Following types were implemented into database:

- Reciprocating air compressor
- Centrifugal compressor

3.4.3. Boilers

Following types of boilers were implemented into database

- Small package boiler
- Large package boiler
- Field erected boiler
- Waste boiler

For first three types crucial parameter was power, but instead of power for waste boiler volumetric flow is considered as primary parameter.

3.4.4. Turbines

The crucial parameter for turbines were power. Following types of turbines were implemented in the database

- Gas turbine
- Steam turbine

3.4.5. Generators

Only one type of equipment was described in this equipment family. The crucial parameter is power.

3.5. Conclusions and final remarks

Eight equipment families were described and implemented into the database. It can be observed that the first two families were described more detailed and considering more possible options and factors. The reason was the necessity to more detailed economy analysis of heat exchangers and electrostatic precipitators in retrofitting scenarios. Remaining equipment described in this chapter gives overall concept how much it can cost initially without including any extra options. However in future database can be expanded and more detailed analysis as well as new equipment families can be introduced into it.

4. Theoretical introduction to electrostatic precipitator systems

As it was mentioned in chapter before, the retrofitting scenarios presented in the project are strongly based on redesigning or installing new filter equipment units. In this chapter only basic information will be provided and explanation on the most crucial parameters of the ESP systems will be explained. This information is required to understand what has the strongest influence on the efficiency of the dust removal systems.

4.1. Main parameters described electrostatic precipitators

Following parameters determine the most important things which need to be taken under consideration during designing the ESP process. However, they should not be confused with these parameters which has an influence on the ESP efficiency. These one will be presented in the next sub-chapters (Mussatti, 2002)

4.1.2. Flue gas properties

The most important parameters of flow should be taken into consideration. These are: volumetric flow rate, temperature, pressure, chemical properties and compounds. In some cases more specific information like corrosiveness can be necessary. To simplify the process of implementation of new ESP system, the data from similar power plant or industrial sectors can be helpful. (Mussatti, 2002)

4.1.3. Collection and discharge electrodes

There are several rules how to install and design electrodes across the ESP system. The most important are to keep proper distance between them. The length is normalized and is set at the level of design of the ESP. For discharge electrodes it is important to cover the top by the shroud to minimize the risk of sparking and metal erosion (Mussatti, 2002)

4.1.4. Specific collection area (SCA)

This parameter should not be confused with the collection area of ESP. The main difference between them is that SCA is used in the process of design and is expressed as area per volumetric flow.. SCA has strong influence on the cost of the whole ESP system. Too high SCA will cause too expensive materials and may influence negatively the economical aspect of the whole investment. (Mussatti, 2002)

4.1.5. Aspect ratio

One of the more important parameter is the aspect ratio. It expresses the ratio between the length and the height of the ESP surface. To keep the highest possible efficiency it should be in the range between 1.3 and 1.5, for the biggest ESP systems, the ratio oscillates around 2. (Mussatti, 2002)

4.2. Main parameters determining efficiency of electrostatic precipitators

The collection efficiency of ESP systems is determined by the following equation (Theodore, 2008):

$$\eta = 1 - exp^{\frac{(-V_{mig} \cdot A)}{Q_{flow}}} \quad (12)$$

Where:

V_{mig} is the migration velocity expressed in m/s
A is the collection area expressed in m^2
Q_{flow} is the volumetric flow rate expressed in the m^3/s

Volumetric flow and collection area seems to be obvious and does not need any further explanation, the migration velocity is better explained in the section below.

4.2.1. Migration velocity

Migration velocity is a dust related parameter and is determined as the velocity of single particle suspended in the gas which is affected by electric field. This velocity is expressed by the formula below, however in practical applications this value is often assumed and taken from tables. (Jędrusik, 2012)

$$V_{pm} = \frac{qEC}{3d\mu\pi} \quad (13)$$

Where:

q is the unique parameter of the particle which describes its behaviour in the electric field [C]
E is the average field intensity, it is constant value and is equal to $1{,}602*10^{-19}$ [V/m]
C is the Cunnigham correction factor [-]
d is the diameter of the particle [m]
μ is the gas viscosity [kg/ms]

As it was mentioned previously, the migration velocity values are tabularised. For the most common types of dust following values are used.

Table 7. Most common values of migration velocity for given particles (Theodore, 2008)

Dust	Migration Velocity (m/s)
Zinc Oxide	0.02-0.03
Sulfuric Acid	0.08-0.16
Metal Oxides	0.02-0.03
Calcium Carbonate	0.04-0.05
Smoke Fume pit coal furnace	0.02-0.11
Fly ash from lignite furnace	0.18-0.25
Blast furnace dust	0.05
Smelter dust	0.07-0.09
Blast furnace dust	0.05

4.3. Summary of the ESP efficiency

This part contains the main information about parameters used in next chapter. In the table 8 common values observed in the ESP systems are presented; however it is important to notice, that these are only suggested values and every case should be considered individually. Moreover, the data refer to 1987 and currently in some extent they may be outdated (e.g., in the field of the velocity) . (Theodore, 2008)

Table 8 Typical values for ESP systems (Theodore, 2008)

Parameter	Range (metric units)	Range (English units)
Distance between plates (duct width)	20-30 cm (20-23 cm optimum)	8-12 in. (8-9 in. optimum)
Gas velocity in ESP	1.2-2.4 m/s (1.5-1.8 m/s optimum)	4-8 ft/sec (5-6 ft/sec optimum)
SCA	11-45 m^2/1000 m^3/h (16.5-22.0 m^2/1000 m^3/h optimum)	200-800 ft^2/1000 cfm (300-400 ft^2/1000 cfm optimum)
Aspect ratio (L/H)	1-1.5 (keep plate height less than 9 m for high efficiency)	1-1.5 (keep plate height less than 30 ft for high efficiency)
Particle migration velocity	3.05-15.2 cm/s	0.1-0.5 ft/sec
Number of fields	4-8	4-8
Corona power/flue gas volume	59-295 watts/1000 m^3/h	100-500 watts/1000 cfm
Corona current/ft^2 plate area	107-860 microamps/m^2	10-80 microamps/ft^2
Plate area per electrical (T-R) set	465-7430 m^2/T-R set (930-2790 m^2/T-R set optimum)	5000-80,000 ft^2/T-R set (10,000-30,000 ft^2/T-R set optimum)

Source: White 1977.

5. Retrofitting scenarios

This chapter presents actual actions which were taken to increase the efficiency of the Lillesjoverket power plant in Uddevalla. It contains two retrofitting scenarios. The first one refers to the flue gas cleaning system and the influence of the resulting fouling on the temperature at the inlet to the SCR system. The second one refers to primary air heating and also describes how the fouling problem of heat exchanger affects the usage of steam required to heat up the air before the combustion.

Both scenarios will be described on the following way:

1. Description of problem
2. Data extraction
3. Methodology
4. Results and economy analysis
5. Conclusions

5.1. Retrofitting scenario 1: Analysing and eliminating problem of fouling in gas/gas heat exchanger.

5.1.1. Description of problem

The analysed system consists of three heat exchangers, electrostatic precipitator, fan and SCR reactor system. The problem propagates from the ESP system to the SCR. Because of the fact that the system was implemented several years ago, its efficiency dropped from the nominal to the lower level. It causes that increasing amount of particles remains after separation and fouls the heat exchanger 1 (figure 16). Fouling film increases the thermal resistances on the tubes causing the decrease of the overall heat transfer coefficient. The consequence is that it causes decreasing temperatures in the whole analysed system. Despite the steam usage which needs to be increased, it can also lead to the severe problem with the SCR reactor.

The inlet temperature to SCR reactor is strictly described and remains in the range between 195°C to around 230°C. The upper limit is not the problem in this case. However, if the temperature drops below 195°C, the ammonia reaction cannot occur and the bypass which causes omitting the SCR reactor needs to be used. It is really uncomfortable situation for the power plant since the SCR (selective catalytic reduction) system is responsible for cleaning exhaust gases from NO_x particles. In case where it is not used, all the hazardous particles remains in the exhaust gases and are directed to the chimney which can cause serious problems with the regulations and limiting hazardous gases policies.

By investigating the problem and estimating current efficiency of the ESP and searching the possible methods to increase this efficiency, the problem of fouling should be eliminated, what in consequence primarily should lead to stabilize the temperature at the SCR inlet and if it is possible to save steam used in the heat exchanger 3 (figure 16). Saved steam can be redirected to heat and electricity production and increase the total income and efficiency of the power plant.

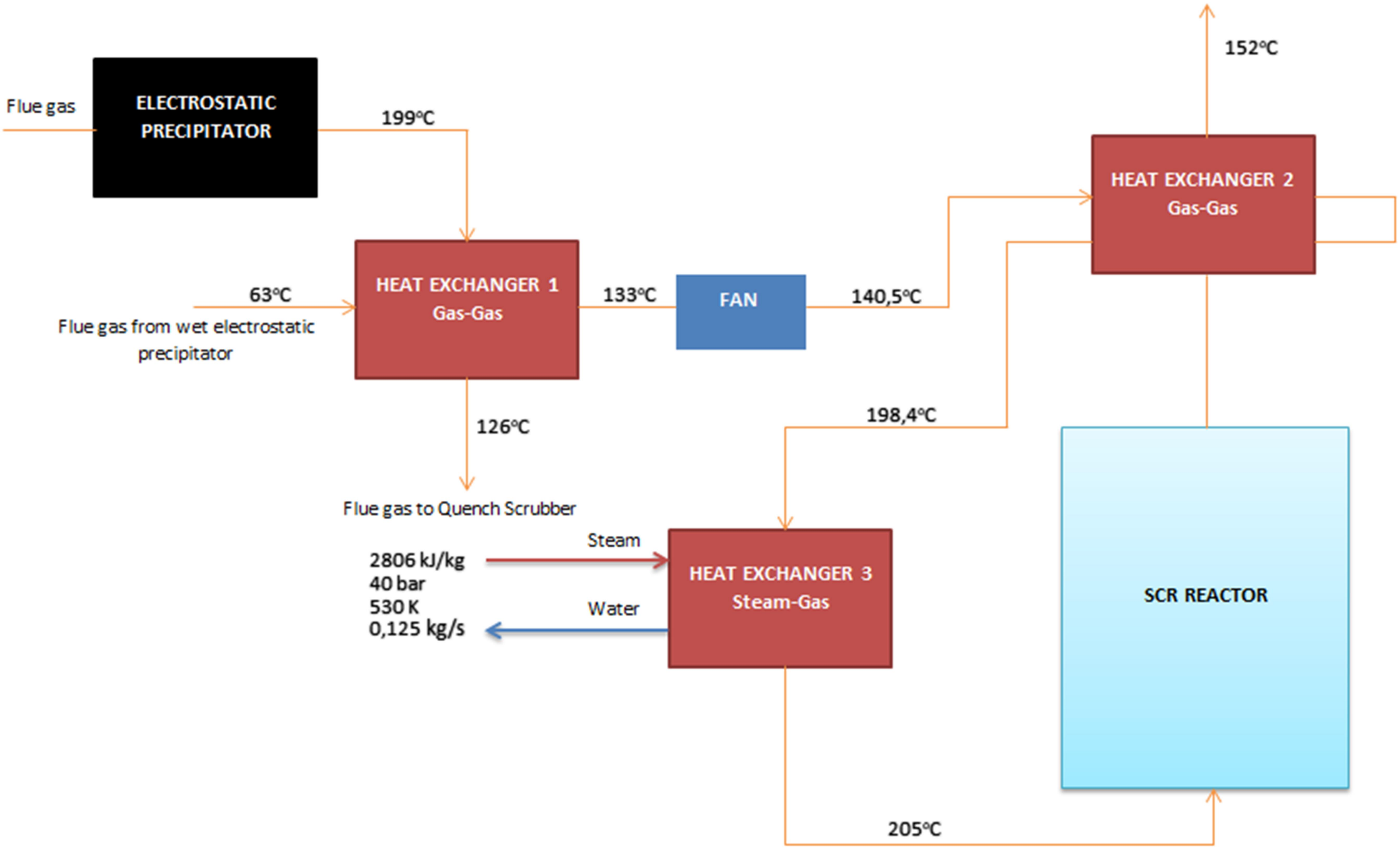


Figure 6 Scheme of the analysed system

5.1.2. Data extraction

To correctly extract the data one important thing had to be noticed. Heat exchanger 1 is cleaned twice per year. So after every cleaning the heat transfer rate should be the highest, since there is no fouling film on the tubes after that. So directly after that process, the temperature of flue gases which are directed into the fan should be the highest. And opposite – directly before the cleaning it was expected that the tubes will be contaminated by dust, so it will lead to the lowest heat transfer rate, which in consequence causes the flue gas temperature directed to quench scrubber to be the highest, and the temperature directed to the SCR reactor to be the lowest. The temperature of exhaust gases after ESP system is kept constant equal to 199^{o}C.

By observation the chart below, the described situation can be noticed:

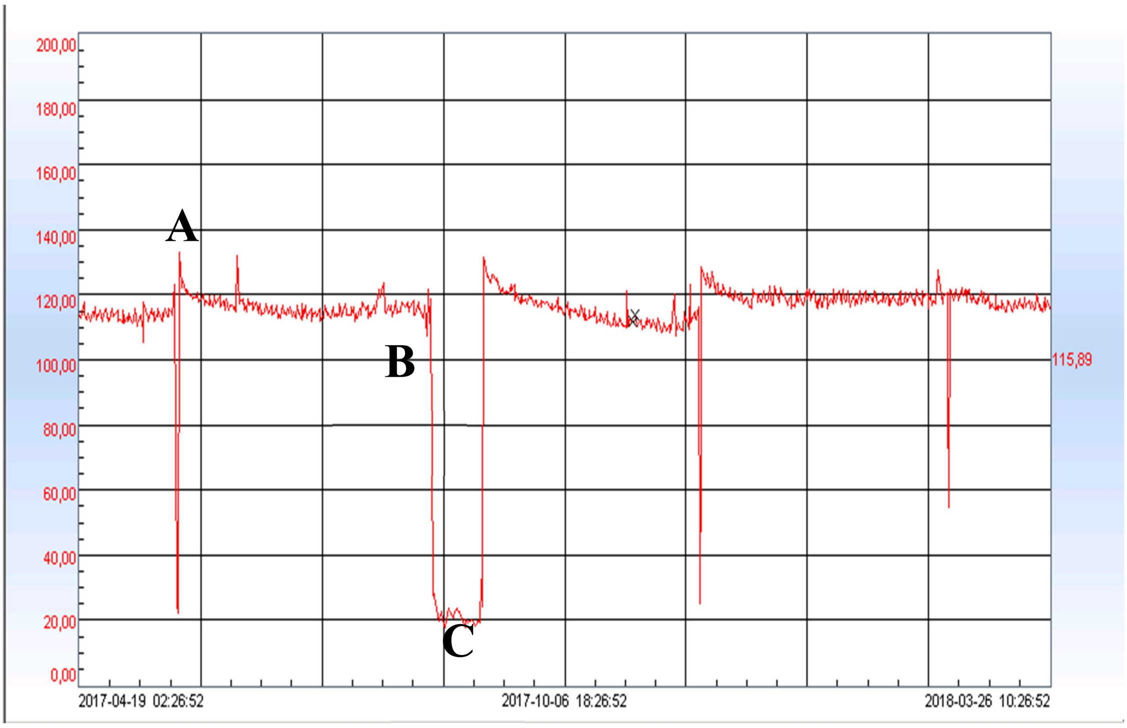


Figure 7 Temperatures of cold stream at the outlet of HX1

Figure 13 presents the outlet temperature of the cold stream in the heat exchanger 1. Three important points can be determined on it:

A – The highest temperature directly after heat exchanger cleaning when the heat transfer coefficient between hot and cold stream is the highest

B – The lowest temperature of the cold stream at outlet of the heat exchanger 1, when the heat transfer coefficient between the streams is the lowest.

C – Maintenance break – time required to clean up the HX1, it can vary between 1 day (most common) to 3 days (usually in May there is bigger maintenance break which lasts 3 days, presented in the Figure 17

For developing the model, data in the time range between **A** and **B** were used. At point **A** it was assumed that the heat exchanger works as the ESP collection efficiency would be 100% (i.e., there is no fouling film on the heat exchanger 1 directly after cleaning, so the ESP collection is considered as an ideal). Next challenge was to estimate the filter collection efficiency when the highest problem of fouling exists. It must be noticed here, that this estimation is strongly approximated since there are no sensors or measurement instruments which evaluates the amount of dust after ESP in the power plant.

After extracting the data for the outlets of heat exchanger 1, data was filtered and gross errors were removed. Data contains a lot of records so it seems to be unreasonable to present it in this report. It is presented in the Excel spreadsheet: *retro1.xlsx* in the worksheet: *temperatures in system*

5.1.3. Methodology

As it was mentioned before, the first task was to estimate the current collection efficiency of the ESP filter. In the chapter 4, it was written that this efficiency is function of three parameters: collection area, volumetric flow rate of gas and migration velocity. The most challenging problem was to estimate the migration velocity of particles in the exhaust gases. Since it is waste-to-heat power plant, the fuel contains a lot of different compounds which are combusted; however the chemical composition of these particles is not measured.. In this situation it was decided to use the worst possible scenario. Based on reports from the company's laboratory, it was noticed that combusted wastes often consists zinc compounds which has the lowest migration velocity..

From the technical documentation of the ESP filter, the total collection area was extracted.

Volumetric flow rate of exhaust gases was collected from the control room system.

Table 9 ESP efficiency parameters values

Parameter	Value
Migration velocity	0,03 m/s
Collection area	2700 m^2
Volumetric flow rate of exhaust gas	79000 Nm^3/h

By knowing these three parameters and using the formula 12:

Collection efficiency was estimated on the level of 88%, what in fact is really low efficiency. New systems have efficiency around 99,5%

This efficiency will be taken into further consideration, however table 10, presents how the migration velocity affects on the collection efficiency if not worst case is realised

Table 10. Dependancy between migration velocity and collection efficiency for current ESP

Migration velocity [m/s]	Collection efficiency
0,03	88,00%
0,04	94,10%
0,05	97,10%
0,06	98,50%
0,07	99,20%
0,08	99,60%

So at this time it was known that directly after cleaning, the ESP efficiency is assumed at 100% and directly before cleaning it is estimated as 88%.

This knowledge allowed to calculate the heat transfer coefficient for the case of 100% (best case) and for case of 88% (worst case); a linear function was used for interpolating values between these two points. This function shows the dependency between the heat transfer coefficient and ESP collection efficiency and linearly shows how the change of 1% of efficiency affects on the heat transfer rate.

To estimate the heat transfer coefficient following parameters were required:

- Heat load of heat exchanger 1
- The area of heat exchanger 1
- Logarithmic mean temperature for streams which flow through heat exchanger 1

Heat exchanger was designed for heat load at level of 2400 kW with respect to no fouling layer inside.

The heat exchange are also was collected from the technical documentation and is equal to 1178 m^2

Logarithmic mean temperatures were equal to 64,39^{o}C and 80,75^{o}C for 100% and 88% of collection efficiency respectively

Thanks to that values, overall heat transfer coefficient **U** could be calculated from equation:

$$U = \frac{Q}{A\Delta T_{LM}} \ (14)$$

So the summary of values for these two present cases is:

Table 11 Summary of calculation heat transfer coefficient for heat exchanger 1

	ESP system			
ESP Efficiency	100%		88%	
Overall heat transfer coefficient, U	34,96	W/m^2K	28,75	W/m^2K
Area, A	1178	m^2	1178	m^2
T hot in	200	C	200	C
T hot out	120,20	C	135,51	C
T cold in	63	C	63	C
T cold out	127,85	C	110,41	C
Logarithmic mean temperature, ΔT_{LM}	64,39	C	80,75	C

By knowing the overall heat transfer coefficient it became possible to evaluate how the ESP efficiency affects the inlet temperature of SCR system. The efficiency drop in the ESP decreases the outlet temperature of cold stream in heat exchanger 1. Consequence of that is decreasing the temperature after compression in fan. It leads to the situation where at the inlet to SCR the temperature drops to the lowest acceptable temperature of around 195°C.

Of course, before the SCR there is steam-gas heat exchanger which increase the inlet temperature of gases, so the easiest solution would be to increase the amount of steam to increase the temperature before SCR system. However, this is not possible for the current sizing of the pipes and valves which already provide the maximum possible amount of steam to the heat exchanger.

From the ESP-heat transfer coefficient derived relationship it was possible to observe what level of efficiency should be implemented into ESP system to obtain safer temperature value at the inlet to SCR reactor. This safer value was estimated as 205°C. It can be observed that increasing the ESP efficiency from 88% to 95% will cause reaching 205°C at the inlet to SCR; increasing it further to 99% will of course increase the temperature too. Consequently, increasing the efficiency would allow to decrease the amount of steam used in heat exchanger 3. Additional steam can be redirected to production heat or electricity and provide additional income.

To increase ESP efficiency, at least one of the three parameters (flow rate, migration velocity or collection area) must be influenced. After discussion with power plant representatives it was set that:

- Flow rate should not be changed since it depends on the amount of waste combusted. Of course volumetric flow rate can vary if the parameters like temperature or pressure will be changed, but after discussion with production manager, it was noticed that these parameters have to remains constant since the power plant is set to predetermined volumetric flow and it should not be changed
- Collection area must be increased to increase the collection efficiency
- Migration velocity depends on the chemical composition of the flow so cannot be changed

Current collection area of the ESP system is at level 2700 m^2 and it corresponds to the value of 88% of collection efficiency. As it was mentioned before another parameters must remain constant.

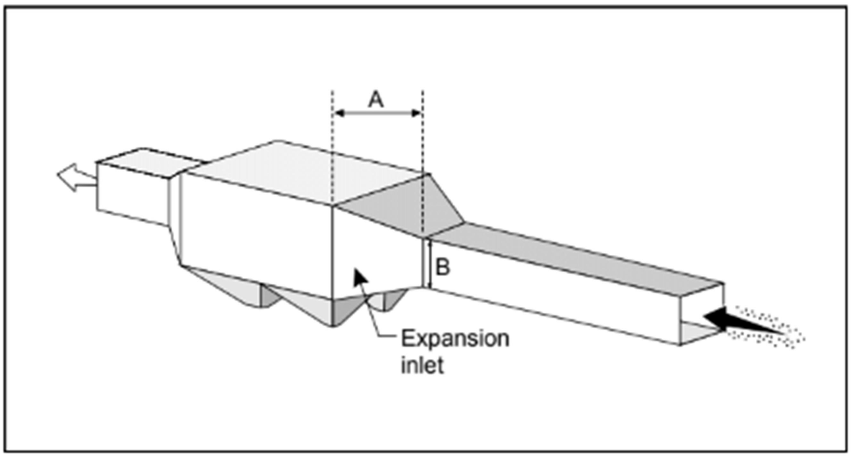


Figure 8 ESP model

The important question is – how much the collection area should be expanded

Two scenarios were considered.

- Increasing the efficiency to 95%
- Increasing the efficiency to 99%

The results of this analysis are presented in the next sub-chapter.

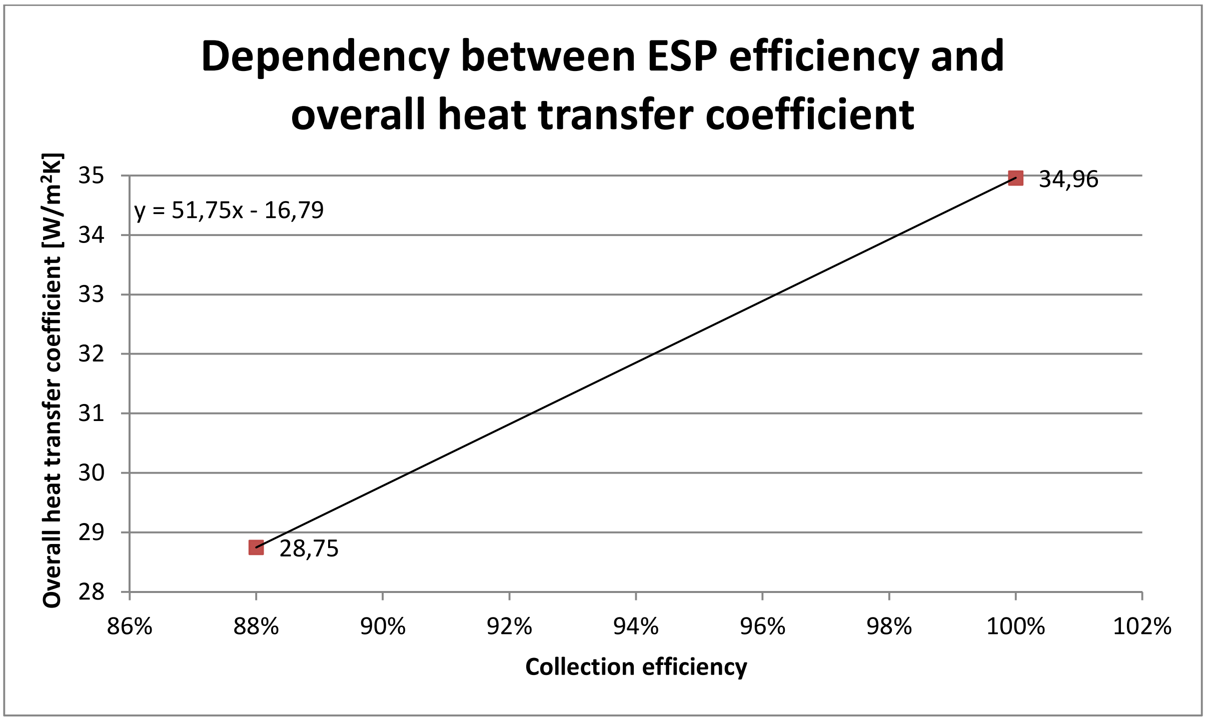
5.1.4. Results and economy analysis.

Following aspects and results are presented in this section:

- Dependency between collection efficiency and overall heat transfer coefficient
- Dependency between overall heat transfer coefficient and temperatures at hot and cold streams outlet in heat exchanger 1
- Dependency between collection area and collection efficiency
- Income analysis
- Cost analysis

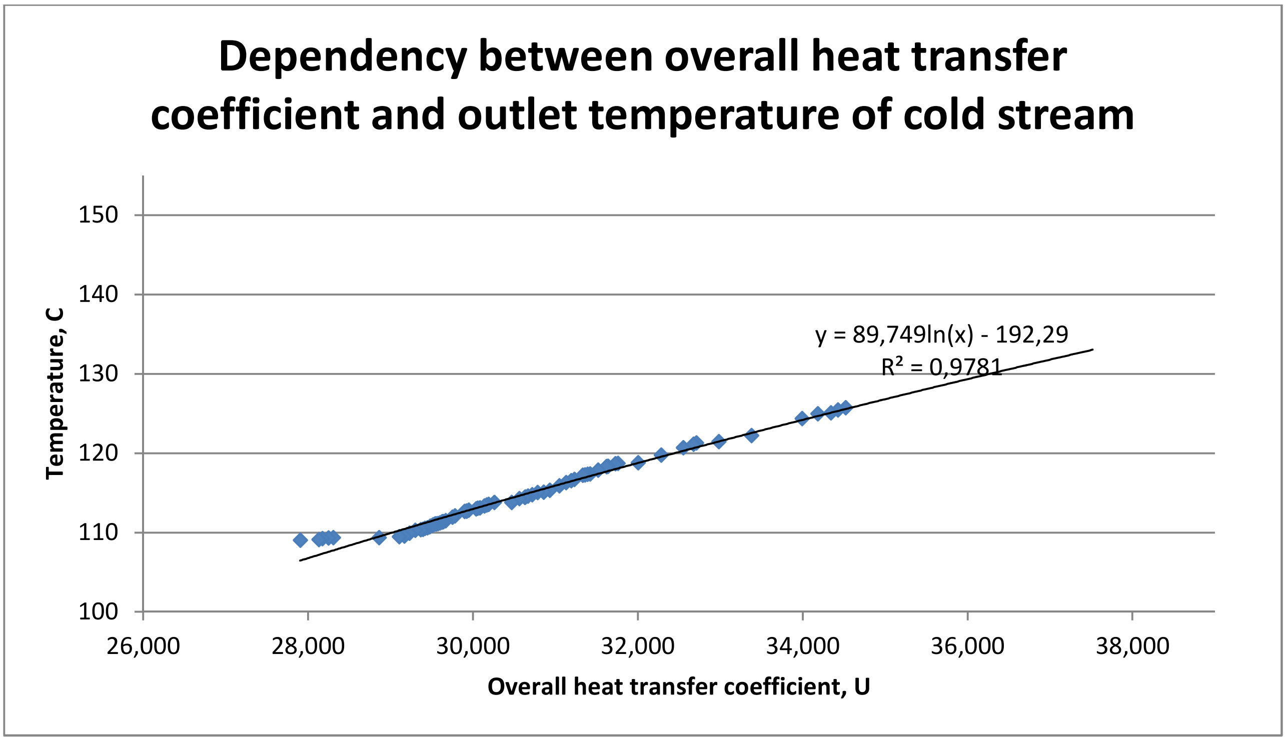
Dependency between collection efficiency and overall heat transfer coefficient

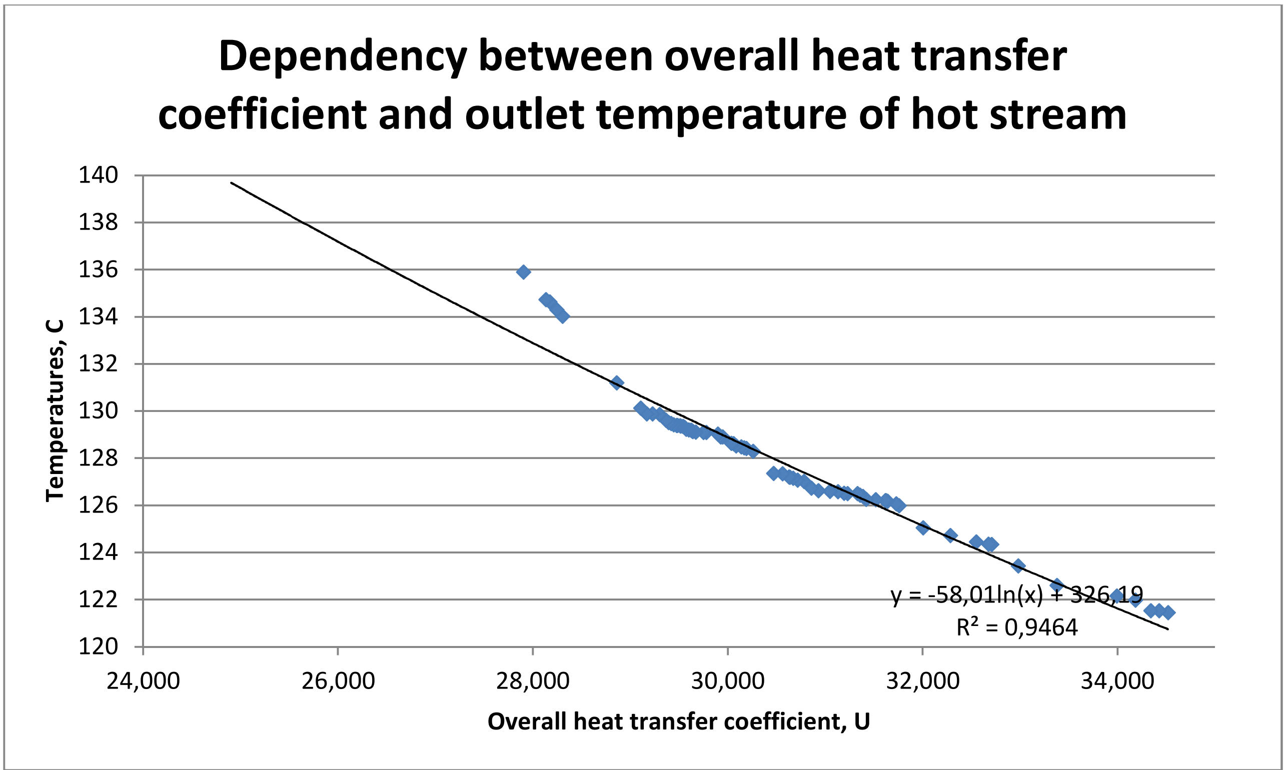
As it was mention in previous chapter the dependency between these two parameters are linear and presented as in the chart below:



Dependency between overall heat transfer coefficient and temperatures at hot and cold streams outlet in heat exchanger 1

The curves below shows how fouling problem affects temperatures at the outlets of heat exchanger 1. Additionally the trend and coefficient of determination were presented.



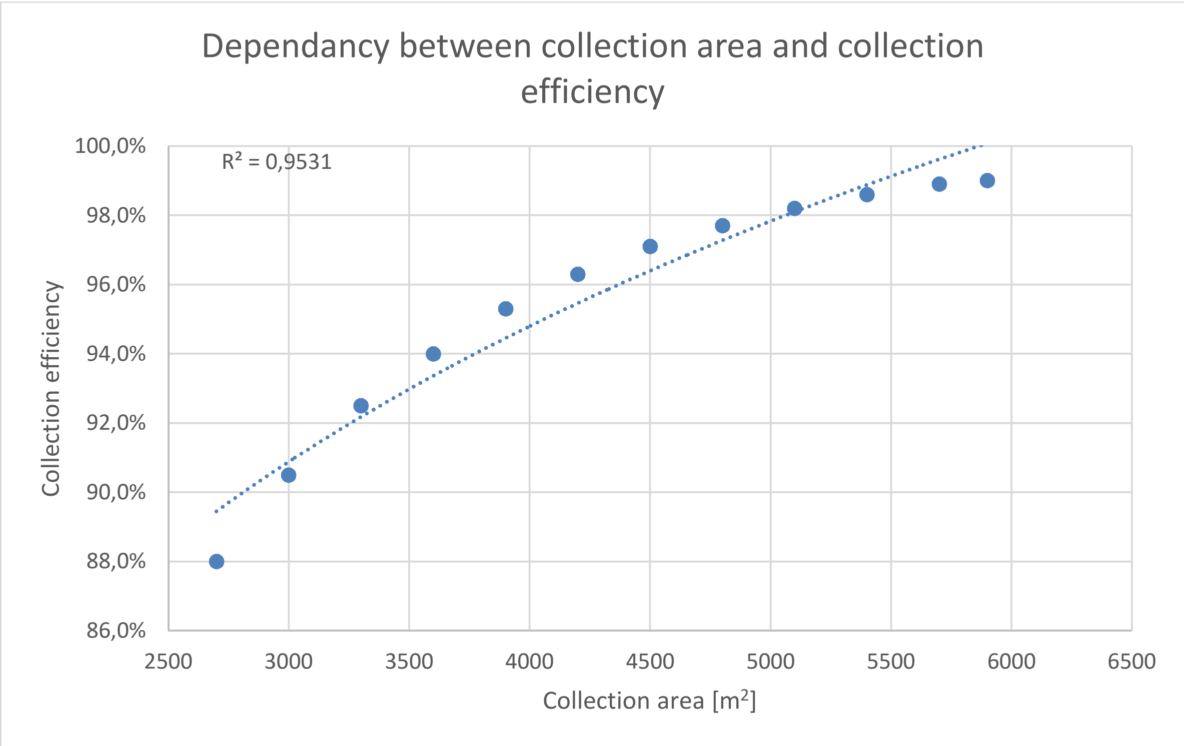


Required collection area to obtain demanded collection efficiency

All results below were obtained by using *ESP_Model.xlsx* which is attached to this report.

Table 12 Dependancy between collection area and collection efficiency

Collection area [m^2]	Collection efficiency [%]
2700	88,0%
3000	90,5%
3300	92,5%
3600	94,0%
3900	95,3%
4200	96,3%
4500	97,1%
4800	97,7%
5100	98,2%
5400	98,6%
5700	98,9%
5900	99,0%



Income and cost analysis

Economic analysis is presented for two scenarios which assumed increasing the collection efficiency to 95% and 99% respectively

1. **Income analysis.**

In this case, there is no additional income for 95% case, since to assure the safe value for the SCR temperature inlet at level of 205°C, the same amount of steam must be used. However, increasing the collection efficiency to level of 99% will provide additional income, since the amount of steam used in heat exchanger 3 can be decreased.

After discussion with power plant representatives, the decision was made that 75% of recovered steam will be provided to generate district heating, and 25% to additional generation of electricity.

During the year, district heating prices vary, thus the average value was taken into consideration.

Detailed income analysis is presented in the table below.

Table 13. Income analysis for 99% of collection efficiency

Parameter	Value	Unit
Saved steam	0,052	kg/s
Enthalpy at inlet	2806,25	kJ/kg
Pressure at outlet	0,6	bar
Temperature at outlet	357	K
Enthalpy at outlet	351,12	kJ/kg
Additional power	127,66	kW
25% for electricity	31,91	kW
75% for district heating	95,75	kW
Electricity per year	279,59	MWh
Heat per year	838,77	MWh
Cost of 1 MWh electricity	370	SEK
Average cost of 1 MWh of heat	465,70	SEK
Additional income from electricity	103448,44	SEK
Additional income from district heating	390616,90	SEK
Total income per year	494065,35	SEK/year

Implementation of proposing solution, allows to save 0,052 kg/s of steam. The steam enthalpy for given parameters is equal to around 2800 kJ/kg, by obtain parameters of steam at the outlet, it is possible to calculate additional energy which can be redirected to the production.

Due to discussion with power plant staff it was set that 25% of additional energy will be redirected to generate electricity and 75% to generate district heating. By multiplying these values by amount of hours per year it was possible to get the amount of MWh per year.

1 MWh of electricity has constant prace at level of 30 SEK/MWh, however price for district heating varies during year. In the winter time the price is higher – due to higher demand for heat in private sector. In the summer time the price is decreased. Presented price is average price between these two values.

2. Cost analysis

The major cost of proposing changes is due to necessity to install additional collection plates. Based on equipment cost database it was possible to estimate the cost of additional plates. It is important to notice that there is no necessity to include additional costs, like preparing the place for new ESP system or installing additional devices and constructions like inlet, stairs or roof of ESP. The current system will not be replaced, but just improved. Table 13 presents the estimated cost analysis for predetermined solution. It is worth to noticed that at this level of prediction – the potential error can vary even up to 35-40%

Table 14 Cost analysis of increasing collection area

Area	Cost of expanding in USD	Cost of expanding in SEK	Efficiency	Payback period in years
2700	- USD	- SEK	88,00%	-
3000	59 581,13 USD	517 760,05 SEK	90,50%	-
3300	116 980,03 USD	1 016 556,42 SEK	92,50%	-
3600	172 465,15 USD	1 498 722,14 SEK	94,00%	-
3900	226 252,53 USD	1 966 134,47 SEK	95,30%	-
4200	278 519,21 USD	2 420 331,93 SEK	96,30%	12,1
4500	329 412,56 USD	2 862 595,11 SEK	97,10%	9,71
4800	349 446,96 USD	3 036 694,07 SEK	97,70%	7,79
5100	413 479,64 USD	3 593 138,04 SEK	98,20%	8,05
5400	476 923,68 USD	4 144 466,81 SEK	98,60%	8,9
5700	539 816,81 USD	4 691 008,08 SEK	98,90%	9,49
5900	581 456,16 USD	5 052 854,03 SEK	99,00%	10,23

From the table 13 it can be concluded that the quickest payback period time is for the option of expanding collection area to 4800 m2, it corresponds to the 97,7% of collection efficiency. In reality it can occur that this efficiency will be even higher, since it is calculated for the worst migration velocity scenario. It is important to mention that dependently on the level of expanding area – the income of saving steam is different. It means that for 97% of efficiency amount of steam saved daily is lower than for 99%, also due to that scenarios below 95% of efficiency does not guarantee any incomes since the temperature before enter into SCR system is below 205^{o}C which was assumed as the minimum temperature which guarantees safety of using SCR now and in future.

5.1.5. Conclusions and recommendations for retrofitting scenario 1

Retrofitting scenario 1 is example where demanded solution can be achieved by low expenditures. However, there are several recommendations for the power plant which could be taken into consideration, to simplify future work and thereby analysis

- Installing the dust measurement after and before ESP system significantly could increase the accuracy of model. Thanks to that implementation, the collection efficiency could be measure directly as a difference between amount of dust at the beginning and the end. Current solution are more or less approximated. Causes of that are formula which based on the migration velocity is not ideal for type of fuel using in the Lillesjoverket
- It should be considered if the collection area should be expanded to fulfil the efficiency level to 95% or 99%. Each of the solution has some advantages and disadvantages which are presented below
  - Efficiency at 99% basically solves problem of heat exchanger cleaning, what allows to save money of course, but what is more important time and protect equipment from decreasing its lifetime
  - Option with higher efficiency allows to generate additional income by redirecting recovered steam to the production section. Additional benefit is to decreasing the load of valve which provide steam to the heat exchanger 3, at this time it operates at full load so there is safety gap in case of emergency
  - 95% scenario must taking into consideration necessity of cleaning, however not so often, it still will require the maintenance. What is more important, ESP system which works at level of 95% cannot be longer considered as ideal. With time, temperatures at the cold outlet will decrease, what will force increasing the steam delivery to heat exchanger 3 and decrease potential income from savings.
  - However it should be taken into consideration that payback period time for 99% scenario is definitely long, 10 years of payback period corresponds to necessity of buying new ESP, since the lifetime should oscillate around this value
  - Due to economy analysis the most economy reasonable option is to increase the efficiency up to level of 97%, by expanding the collection area of ESP to 4700 m^2. Payback period time then is assumed as around 8 years.
  - Despite the fact that 97% of collection efficiency cannot be considered as ideal, it seems that due to assumption of migration velocity, in real this efficiency can be even higher, so additional cleaning costs are not taken into consideration

5.2. Retrofitting scenario 2: Influence of fouling problem, on the amount of energy required to heat up primary air before combustion.

5.2.1. Problem description

The air required to combustion process is taken from the waste container. This has some major advantages. Primarily the air contained in waste container is warmer than ambient air. It means it requires less energy to obtain demanded temperature. The temperature of air required to combustion is 164°C, where the average waste container air temperature is around 19°C. Compare to the average mean temperature in Gothenburg which is around 12°C it gives big energy saving per year. Additionally using the waste container air allows to make overpressure, thanks to that it flows directly to the combustion chambers instead to go to office part of power plant what is undesirable due to odour suspended in this air.

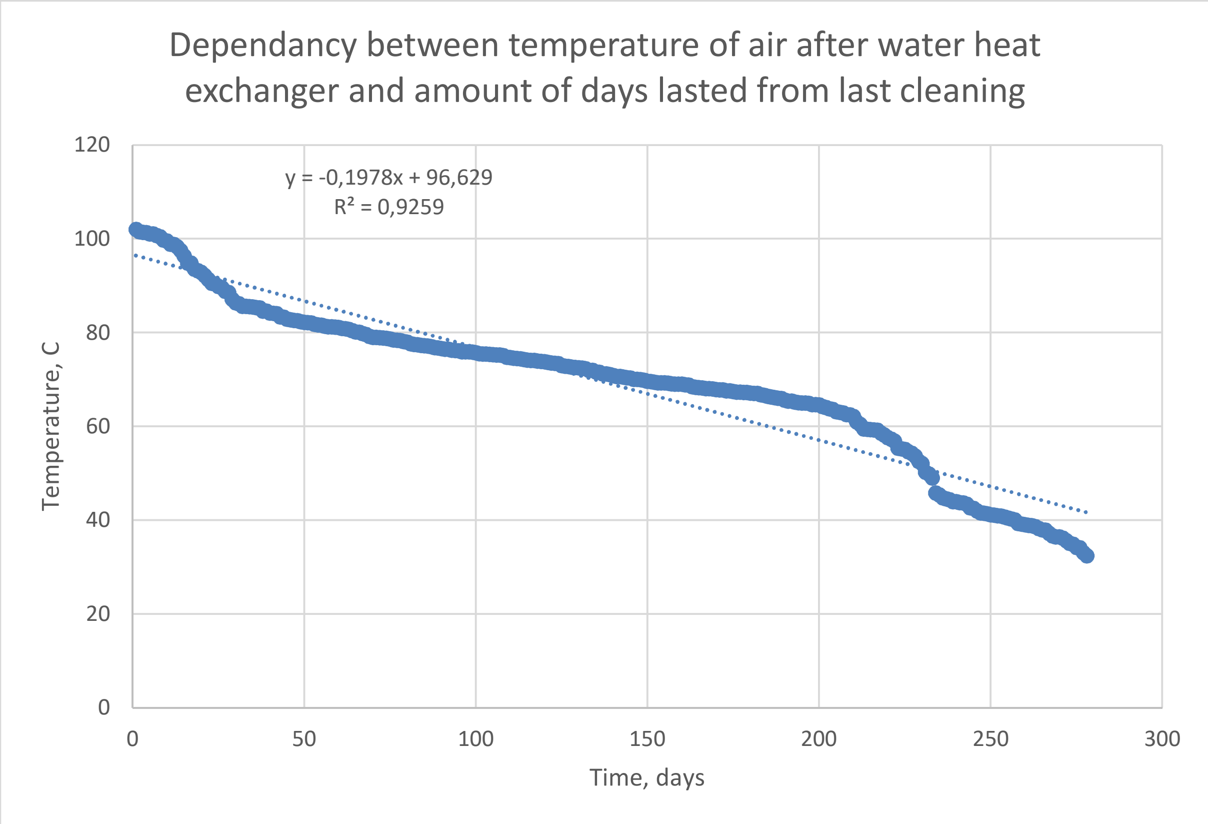
Unfortunately there is one major disadvantage which makes using this air problematic. After unpacking the waste truck, small dust particles are taken into the combustion together with the air. Despite the fact that there are filters which filtrates bigger parts, it is not enough for the smallest particles. This particles fouls the system of heat exchangers used to preheat the primary air (Figure 20). The system contains two heat exchangers as it is presented in the Figure 20. The first one is water-gas heat exchanger, it uses hot water which was used to cool down the furnaces. This heat exchanger is mostly contaminated. The second heat exchanger is steam-gas heat exchanger. By increasing heat transfer coefficient of the first one, it will allow to decrease amount of steam using in the second one – since the target is constant. Primary air needs to be heated to 164°C.

The idea to solve the problem is to install new dust removal system. The analysis was performed for the ESP system and costing was also done for that. All calculation and analysis are presented in the *retro2.xlsx* file attached to this report.

5.2.2. Data extraction

Due to the fact that data extraction is not different from the previous case it is not presented here once more. However some changes needs to be described here.

This time the heat exchangers system is cleaned once per year by external company. Probably due to the measurement instrument errors many measurement points in the scale of 365 days occurred to be gross errors. Values presented by them were unreasonable and needed to be filtrated. One measurement point refers to one day of work. The final amount of measurements is 288 – so it means that close to 80 measurement points were removed. Later the data was filtrated and set from the highest to the lowest. As it is presented in the chart below:



There is visible gap around day 225, what means that many measurement points were removed in this period.

Most variables (temperatures, mass flows) were calculated by using energy and mass balances equations.

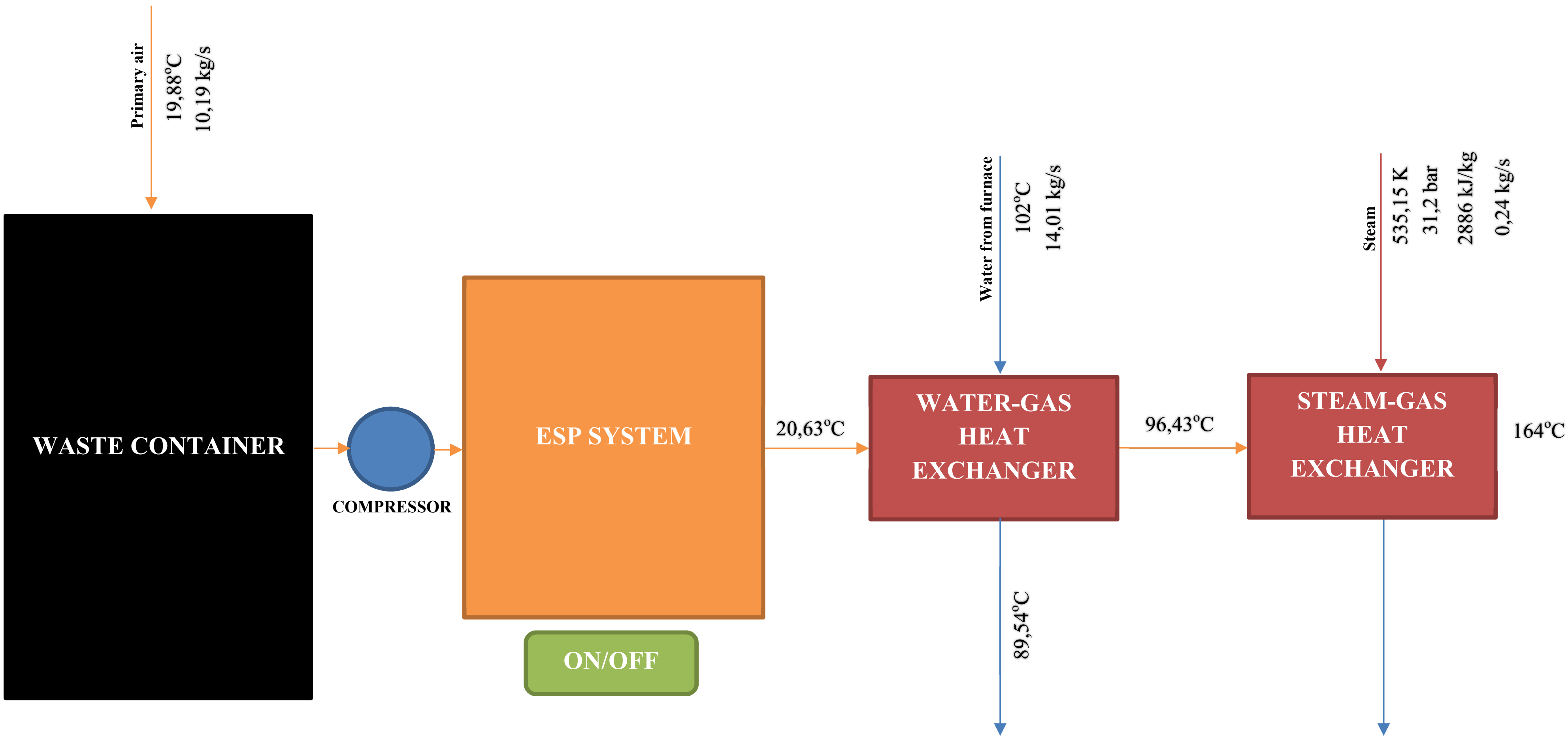


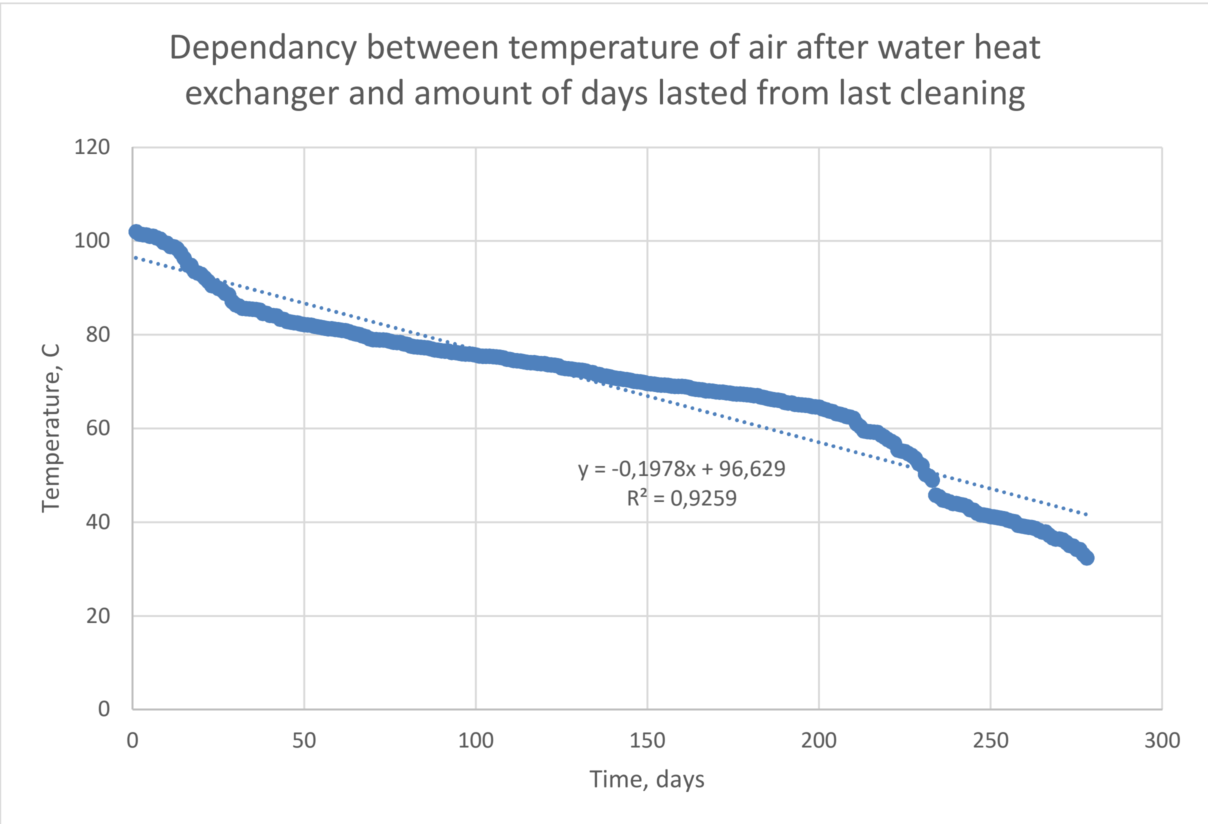
Figure 9 Scheme for retrofitting scenario 2

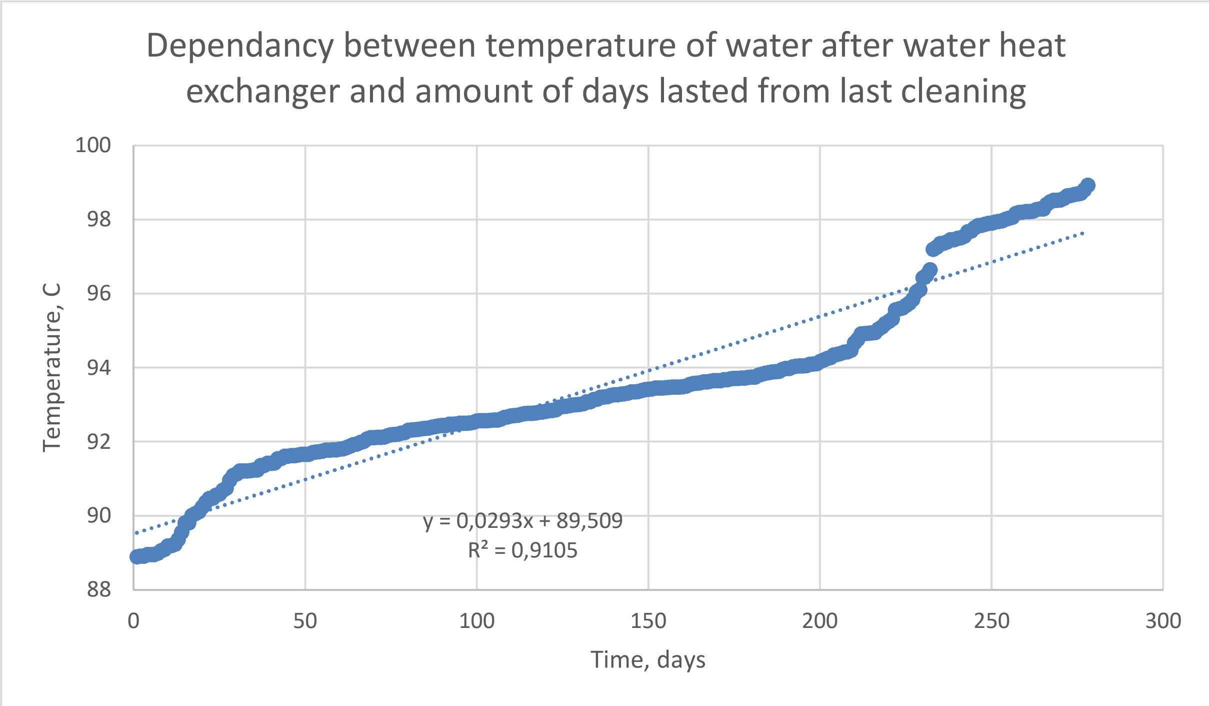
5.2.3. Methodology

After solving energy balances for all heat exchangers and collecting all unknown variables, potential ESP system was adapted. The model *retro2.xlsx* presents how the amount of time after previous cleaning affects on the temperature after the water-gas heat exchanger, and how it leads to increase the amount of steam. Once more time the overall heat transfer coefficient was calculated for the water-water heat exchanger and it was observed how it changes, in the time-scale. Installing the ESP system sets the overall heat transfer coefficient to the highest possible value, namelyso for the value directly after cleaning. In the model ESP has two modes ON/OFF. Disabling the system makes the whole model time dependent.

5.2.4. Results and economy analysis

As it is presented at the charts below, installing the ESP system allows to significant increasing overall heat transfer coefficient. The amount of steam required to heat up primary air decreased by a factor of 2. However in this case there was not existing system, so it must be installed from the initial point, so as it is expected – investment costs will drastically increase.





As it can be observed in the first days after cleaning furnace cooling water releases the highest amount of heat, what in consequence allows to obtain the highest temperature before steam-gas heat exchanger. The amount of fouling layer in the heat exchanger increases with time, what causes additional thermal resistance and in final decreases heat transfer rate between streams.

The amount of saved steam was calculated in the following way.

1. The initial point is the first day after cleaning, then amount of saved steam is equal to 0 and the overall heat transfer coefficient is the highest
2. In the second day, the difference of steam usage for enabled and disabled ESP system were calculated. Absolute value of this difference was multiplied by the steam enthalpy what finally gives the amount of energy saved during day 2
3. The procedure from point 2 was repeated for every next day, when the reference point was always day first, when there is no fouling layer in the heat exchanger and it refers to enabled ESP system or day directly after cleaning.
4. After calculating 288 days, amount of energy was multiplied by 24h to convert the value to MWh
5. Total amount of energy in MWh was summed up and similarly to retrofit scenario 1 divided. 25% was directed to produce electricity and 75% was directed to produce heat.
6. There is no longer necessity to use external cleaning company, so yearly savings was included. According to bills, the cleaning costs around 15000 SEK

The table below present detailed analysis of incomes:

Table 15 Analysis of incomes for retrofitting scenario 2

Parameter	Value	Unit
Steam inlet tempertaure	535,15	K
Steam pressure	31,23	bar
Steam enthalpy	2886,70	kJ/kg
Final temperature of air	164	C
Amount of steam required if ESP is ON	0,2397	kg/s
Amount of energy saved per year	2266,10	MWh
Price for 1 MWh of heat	465,70	SEK/MWh
Price for 1 MWh of electricity	370,00	SEK/MWh
Amount of energy to heat	1699,57	MWh
Amount of energy to electricity	566,52	MWh
Income from heat	791 493,74	SEK/year
Additional income - no cleaning necessity	15 000,00	SEK/year
Income from electricity	209 614,69	SEK/year
Total income	**1 016 108,43 SEK**	**SEK/year**

However as it was mentioned before, investment costs are much higher in this case. They can be divided for three types of costs

- Purchased equipment costs – included equipment, material, instrumentation and freight cost
- Direct installation costs – included all costs connected with installation like mounting, piping, painting etc.
- Indirect costs – all additional costs like engineering maintenance, performance tests etc.

To estimate equipment cost, database presented in the chapter 3 was used. Cost function for ESP system is presented below:

$$Cost(\$) = 891{,}1 * A^{0{,}5776}$$

It is important to mention that area should be expressed in square feet since the initial form of formula was taken from American literature (Turner, 1995).

By using *ESP_model.xlsx* the required area was obtained for the efficiency at level of 99%. It is equal to 14030 ft^2.

Then the equipment cost was presented in the table below. Rest of costs are shares of equipment cost or purchased equipment cost and also was included in the table.

Table 16. ESP cost analysis

Direct cost:		
Purchased equipment cost	**Cost**	**Share of EC or PEC**
ESP cost+auxiliary (Equipment cost)	$ 221 451,20	
Type 304 Stainless steel collector plates and precipitator walls	$ 88 580,48	0,4 of EC
Instrumentation	$ 22 145,12	0,1 of EC
Freight	$ 11 072,56	0,05 of EC
Purchased equipment cost	$ 591 873,21	1,45 of EC
Direct Installation Cost		
Foundation and supports	$ 23 674,93	0,04 PEC
Handling and erection	$ 295 936,61	0,5 PEC
Electrical	$ 47 349,86	0,08 PEC
Piping	$ 5 918,73	0,01 PEC
Insulation for ductwork	$ 11 837,46	0,02 PEC
Painting	$ 11 837,46	0,02 PEC
Direct installation cost	$ 396 555,05	
Total Direct Cost=Purchase Equipment Cost+Direct Installation Cost	$ 988 428,27	
Indirect costs		
Engineering	$ 118 374,64	0,2 PEC
Construction and field expense	$ 118 374,64	0,2 PEC
Contractor fees	$ 59 187,32	0,1 PEC
Start-up fee	$ 5 918,73	0,01 PEC
Performance test	$ 5 918,73	0,01 PEC
Model study	$ 11 837,46	0,02 PEC
Contingencies	$ 17 756,20	0,03 PEC
Total Indirect Cost	$ 337 367,73	
Final cost	**$ 1 325 796,00**	
Final cost in SEK for USD/SEK for May 2018	**11 400 519,78**	
PAYBACK PERIOD	11,22	years

5.2.5. Conclusions and recommendations

- Despite the fact that proposed solutions allows to save over 1 million SEK per year, the investment costs seem to be too high to perform the investment. Estimated payback period time exceed 11 years and it is too long time for repaying.
- However some of costs included in table 12 can be avoided. Company has human resources who can deal with some of the actions mentioned in the table, like painting, performing tests, piping. It depends on the company what it decides to do on its own and what need to be contracted to external subcontractor
- Another thing that need to be considered is the size of the system. It can occur difficult to install the whole system in the relative small and limited space. Another option to solve the problem is to look for more compact solution, however then the detailed cost analysis must be performed before any action
- Similarly to retrofit action 1, it is recommended to install the particle measurement system, the analysis could be more accurate if the sensors were adapted. Additional recommendation is to check temperature sensors at the primary air path, many measurement point remained unreasonable at the stage of extracting data and needed to be further removed from analysis.
- The equipment cost provided by database also should be respected carefully. However including CEPCI index decreases the possibility of error, it needs to be considered that the value of money is rather instantaneous and many factors has influence on it all the time. Not only chemical or engineering aspects, but also geographical (new resource deposits), social (access to human resources) etc. every day affects the price of every single equipment in the world

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A

Appendix A

A1. Data extraction by using ASPEN PROCESS DATA

The collecting the data is possible by ASPEN Process Data system installed as an add-on for Microsoft Excel. The server user has access to all parameters of power plant not only for current time, but also for previous years.

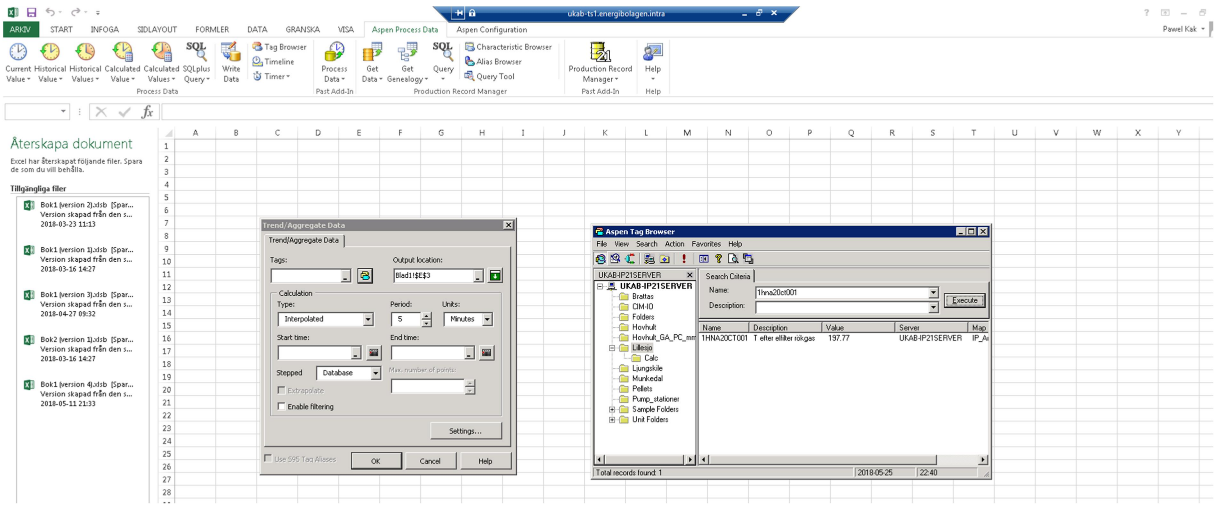

Figure 10 Extracting data system

Every parameter which is measured in Lillesjoverket has its unique code which allows to find demanded parameter in the base. By using this code it is possible to export values in given time range. The overall formula of code is: 1XXXYYX**Z**YYY (ASPEN Technology, 2000)

Where X states for letters, Y for numbers and Z describes types of flow

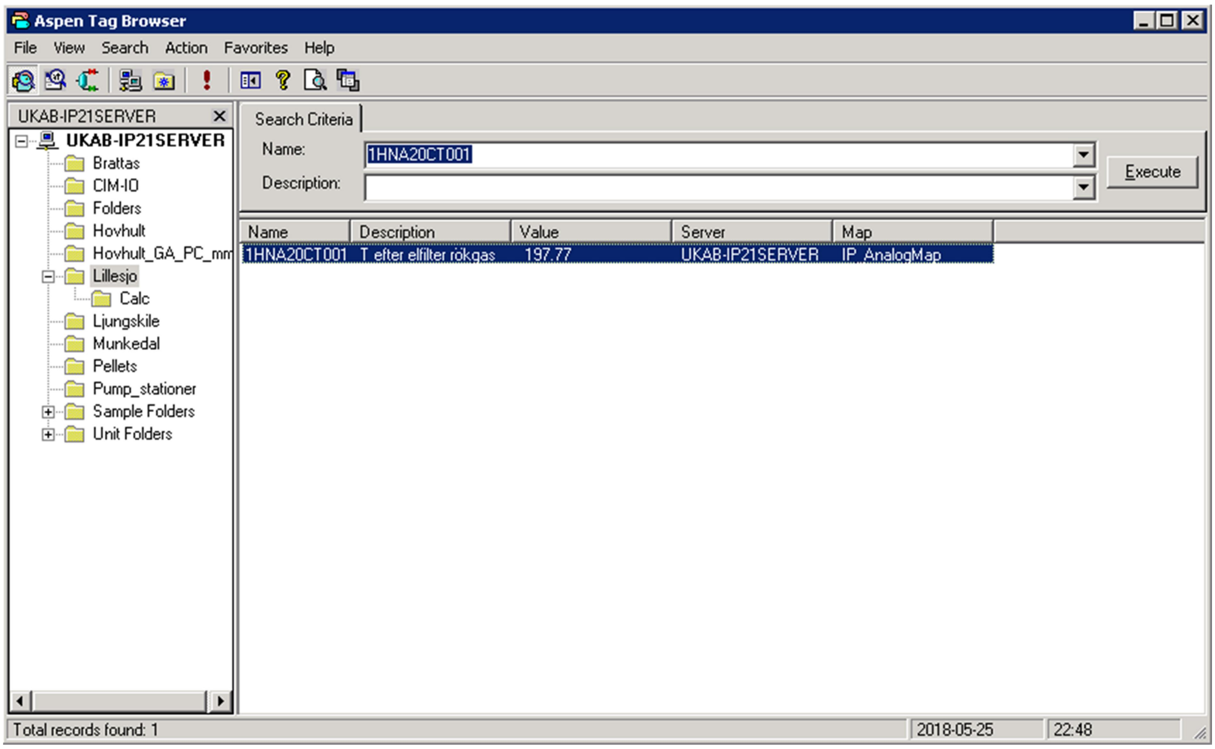

Figure 11 Extracting data system

To simplify the work, types of parameter (flow, temperature, pressure etc.) can be identified by replacing **Z** in formula above by proper letter which symbolise the type (ASPEN Technology, 2000)

T – Temperature

P – Pressure

F – Flow

E – Current or voltage

Q – Power

L – Length

Example: If the parameter is described by code: 1HDWCT001 – it means this measurement equipment measures temperature

Further data visualisation opportunities exist for all measured parameters. Possibility to obtain the chart was really helpful during investigation potential measurements error. Visualisation allows to remove all measurement points which were considered as the gross errors – it means errors which are removed from the total analysis. To do this ASPEN Process Explorer is used. After choosing the proper parameter and obtaining its code, the parameter can be directly drag into the programme and generate the diagram. The time range, scale and more parameters can be set after that as it is presented at pictures below

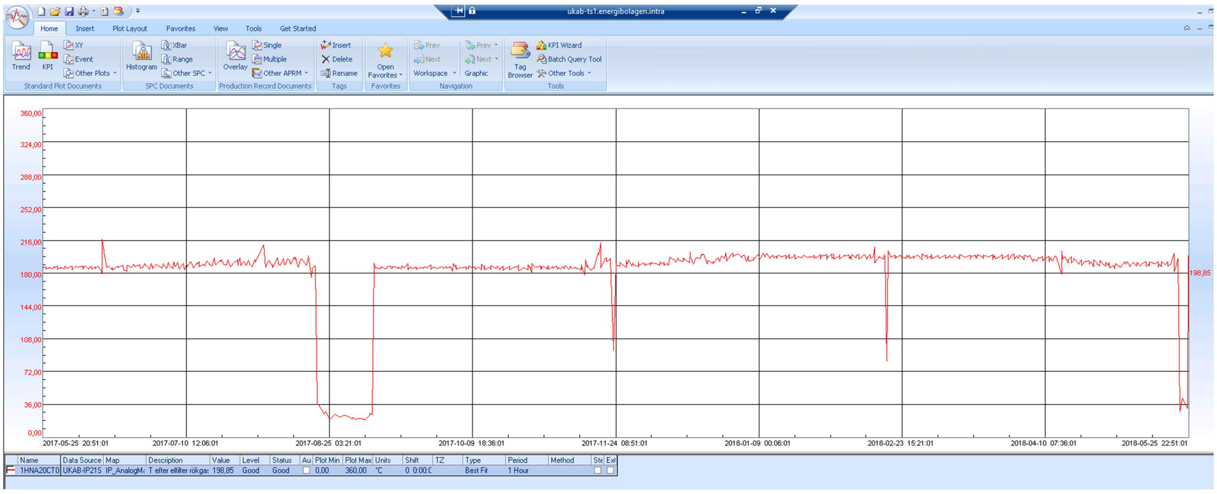

Figure 12 Graphic forms of data representation

Figure 13 Representations of several parameters at one chart

Data extraction system in the Lillesjoverket is easy and user friendly, thanks to that obtaining required data for Ebsilon model or for further retrofitting scenarios was rather simple and does not take significant amount of time. (ASPEN Technology, 2000)

A2. Cost curves used for the costing of some types of equipment in the equipment cost database

In this part of appendix, charts represent cost curve for following type of equipment were collected:

- Medium and low pressure compressors
    - Reciprocating air compressor
    - Helical screw
    - Straight lobe
- High pressure compressor
    - Reciprocating air compressor
    - Centrifugal compressor
- Boilers
    - Field erected
    - Small package
    - Large package
    - Waste heat
- Turbines
    - Steam turbine
    - Gas turbine
- Generators
    - Turbine drive (including boiler&installation)

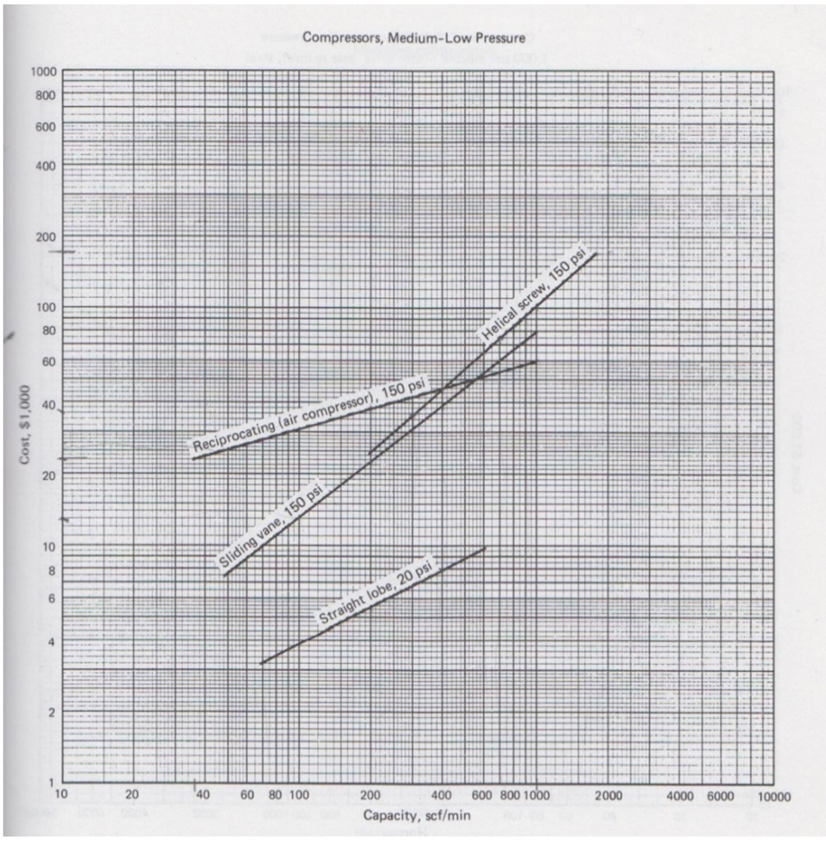

Figure 14 Cost curve for medium and low pressure compressors (Garett, 1987)

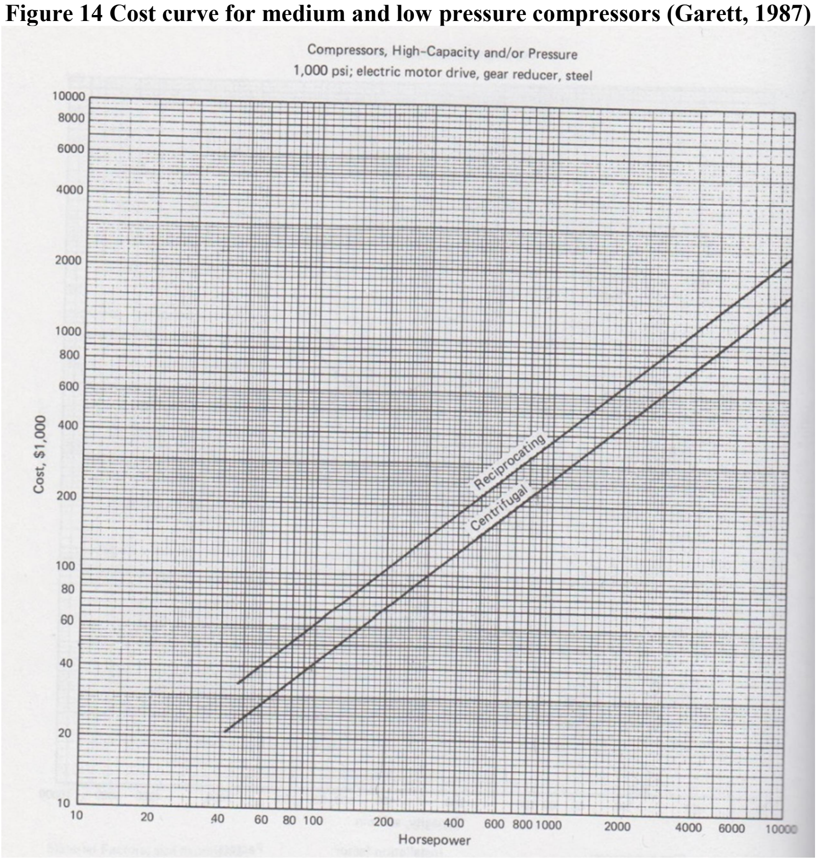

Figure 15 Cost curve for high pressure compressors (Garett, 1987)

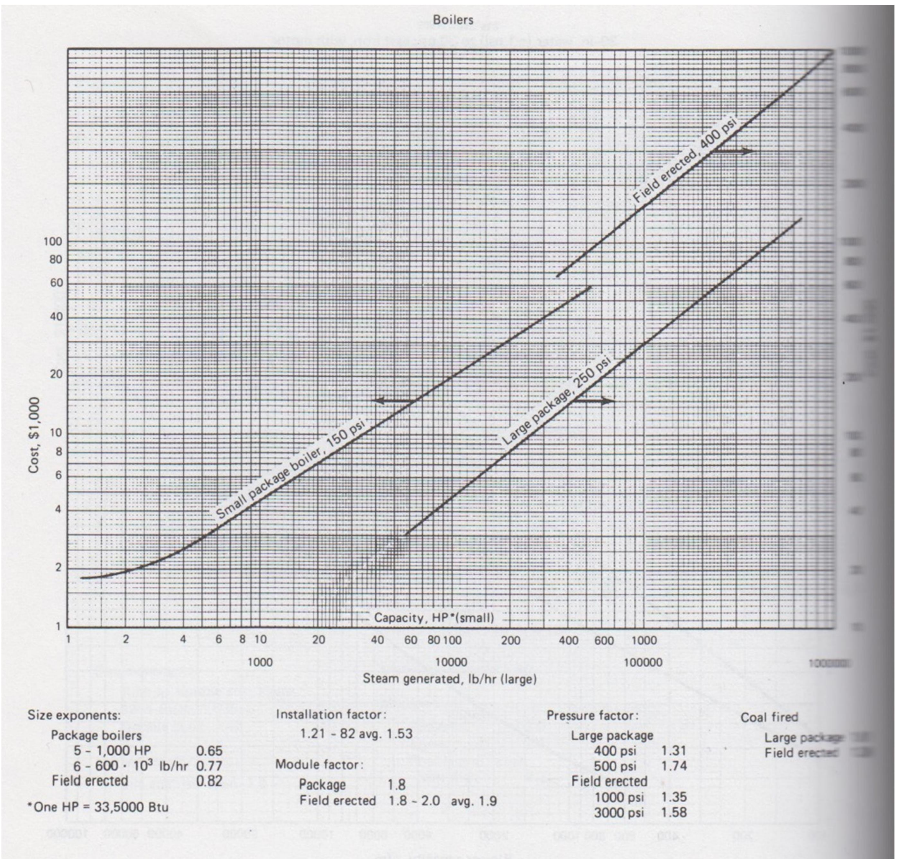

Figure 16 Cost curve for boilers (Garett, 1987)

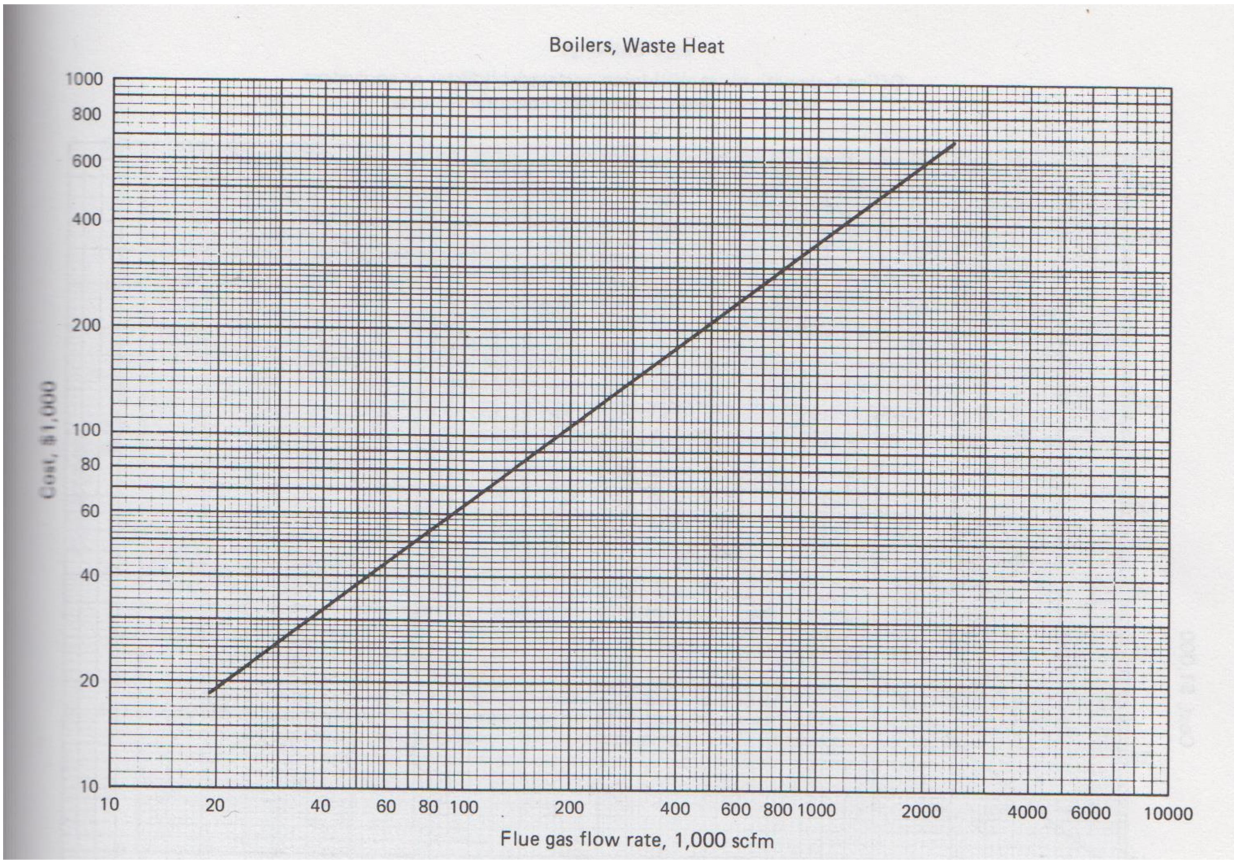

Figure 17 Cost curve for waste boilers (Garett, 1987)

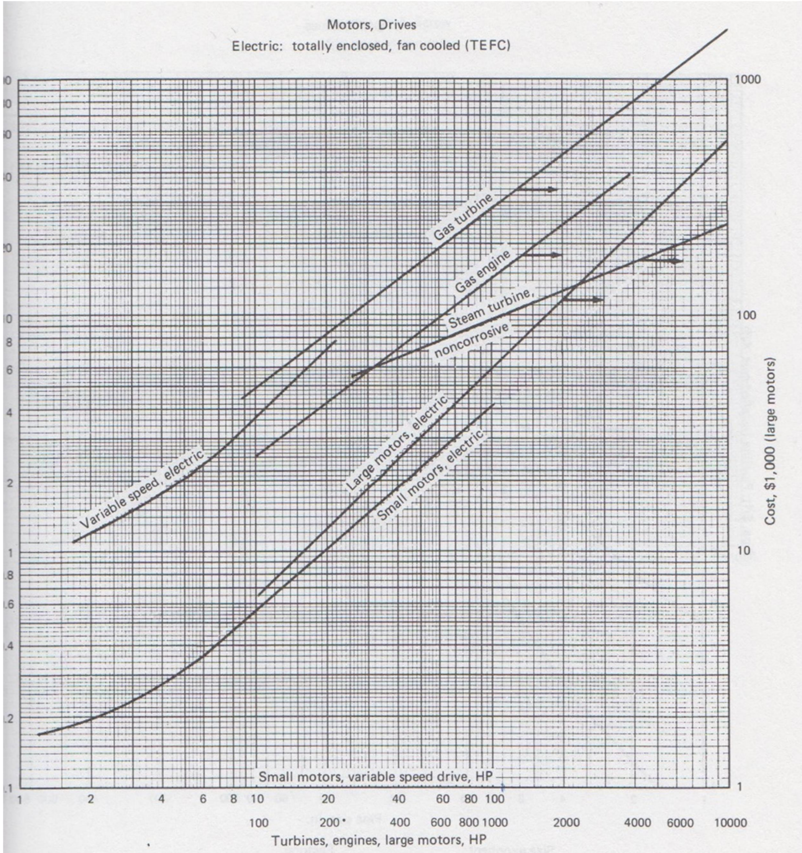

Figure 18 Cost curve for turbines (Garett, 1987)

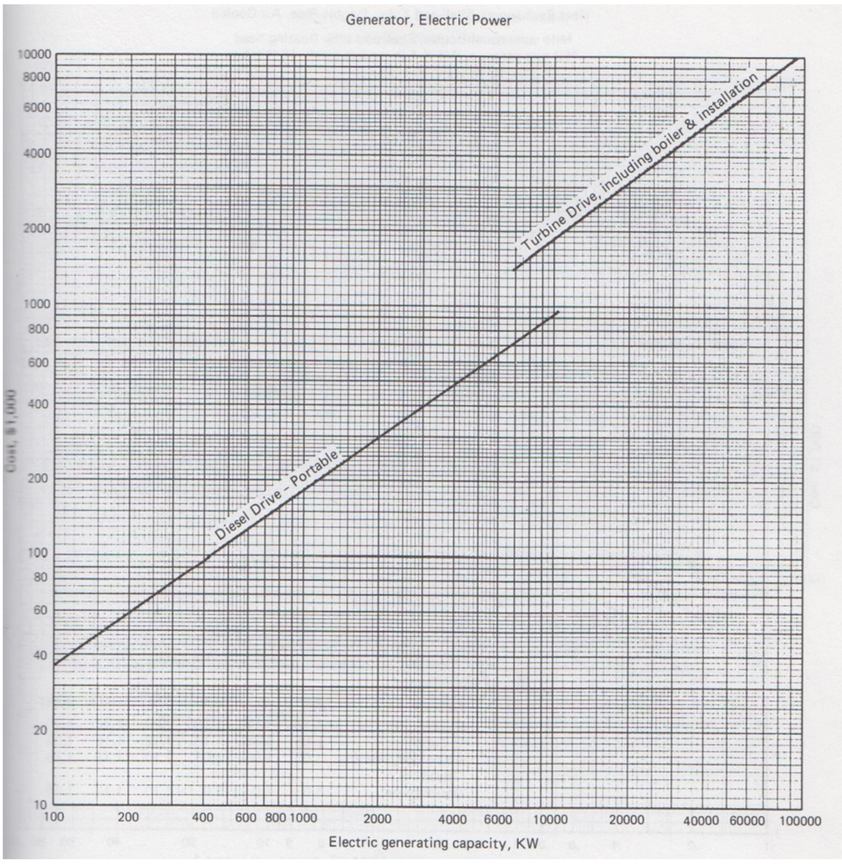

Figure 19 Cost curve for generators (Garett, 1987)