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Industrial Electrical Engineering and Automation

Energy Conservation in Wastewater Treatment Operation

- a Case Study at Sjölunda and Klagshamn WWTPs

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Abstract

Energy conservation is a hot topic in Swedish wastewater treatment operation today. The Swedish Water & Wastewater Association predicts a 10 % energy saving potential in wastewater treatment and German studies indicate the possibility of an even larger potential. Increasing energy costs and stricter environmental requirements forces the Swedish wastewater treatment plants to start working with energy conservation. Both national and international studies indicate that much can be done with existing equipment and small investments.

This master thesis is a study of the energy usage at Sjölunda and Klagshamn wastewater treatment plants, two wastewater treatment plants with one management, in Malmö, Sweden. The report contains inventories of the energy usage at both plants and an energy conservation plan for each of them. The report also discusses the usage of performance indicators for energy conservation in wastewater treatment operation.

Keywords: Energy conservation, wastewater treatment, performance indicators, energy consumption, energy inventory

Preface

This master thesis completes our studies at the Master of Science programme in Electrical Engineering at the Faculty of Engineering, Lund University. This work has been carried out in cooperation between Malmö Water and Wastewater Works and the Department of Electrical Engineering and Automation at Lund University.

We would like to express a special thank you to our supervisors at Lund university, Dr Christian Rosén and Dr Ulf Jeppsson and to Ulf Nyberg, our guide at Malmö Water and Wastewater Works. We would also like to thank the staff at Sjölunda and Klagshamn wastewater treatment plants for answering our endless stream of question.

Sjölunda wastewater treatment plant
September 2007

Joakim Rydh

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1 Introduction

It is becoming more and more apparent that the ways of the modern society of today have heavy impact on the environment. The large energy consumption is part of the problem. To preserve the environment there has to be changes in all parts of the society. Much hope is directed towards modern and future technology. A lot of effort is spent on researching more environmentally friendly methods of power generation and on finding alternatives to the use of fossil fuels. This is all very important, but there are other ways as well of reducing the energy consumption. Much can be done with already existing equipment. If energy conservation was a part of everyone's thinking much would be achieved. This is the topic of this master thesis. The processes at two Swedish wastewater treatment plants (WWTP) will be studied from an energy conservation perspective to see what can be done to decrease energy consumption without affecting the quality of the treatment.

1.1 Background

Wastewater treatment plants consume about 1 % of the total electrical energy consumption in Sweden. Many of them are old and were built when saving energy was not such a large issue as it is today. A new awareness together with increasing demands from the government and increasing electricity costs makes it of immediate interest to reduce the energy consumption. Studies from German wastewater treatment plants show a saving potential of about 35 % of the total consumption (Kjellen - Andersson, 2002).

1.2 Objectives

This master thesis has three main objectives that are closely tied together. The first objective is to do an energy usage inventory at Sjölunda and

Klagshamn wastewater treatment plants in Malmö. The second objective is to determine energy conservation plans for the two plants, based on the energy usage inventories. The third objective is to study the definition and use of performance indicators as tools for energy conservation.

1.3 Target group

The main target group for this master thesis is students in the later years of MSc in engineering programmes. Another target group is staff at wastewater treatment plants. Most people with a technical background should be able to comprehend the main part of this report.

1.4 Outline

This master thesis is divided into four parts. The first part, which consists of Chapters 3, 4 and 5, describes the wastewater treatment process in general and the processes at Sjölunda WWTP and Klagshamn WWTP in particular. General aspects on energy conservation in wastewater treatment are discussed in this section as well. This section is primarily for readers who are not familiar with the methods of wastewater treatment. Dividing the first part into three chapters gives the reader reading options based on previous knowledge, and helps the reader, unfamiliar with wastewater treatment, by first describing the basic processes and then providing an example of a real process setup.

The second part is related to the energy usage inventory where the processes at Sjölunda WWTP and Klagshamn WWTP are studied and the energy consumption of the different stages in the processes is derived. This part is presented in Chapter 6.

The third part is about the development of the energy conservation plans as well as describing the plans themselves. This part is presented in Chapter 7.

The fourth and last part discusses performance indicators. This part is discussed in Chapter 8.

As an introduction to the four main parts the general work methodology is presented in Chapter 2.

1.5 Clarifications and delimitations

This report concentrates on electrical energy. Heat and chemical energy will not be considered. If nothing else is stated, energy means electrical energy in this thesis.

2 Methodology

This chapter aims to describe the methods used during the work with this master thesis. The wastewater treatment process will be evaluated in process stages. The choice of stages is due to the nature of the treatment process and as well, the placement of electrical power meters at Sjölunda WWTP. Some categories apply only to one of the WWTPs. As far as possible the same structure will be used at both Sjölunda WWTP and Klagshamn WWTP to facilitate comparison between the two.

2.1 Energy usage inventory

The first step is to perform the energy usage inventory which will basically end up as a ranking of the process stages above with respect to energy consumption. The ways of deriving this ranking will be different for Sjölunda and Klagshamn WWTP and will be described below.

2.1.1 Work flow

First the possibilities of each WWTP have to be determined. Which information exits? Which is the best way to determine the energy consumption of the different process stages? There is a number of different ways to determine energy consumption. The ones used in this report will be described in Section 2.1.2.

The next step is to actually derive the energy consumption of each stage and to calculate the percentage of the total energy consumption.

The last thing to do is to estimate the errors. What sources of error exists and how big errors can be introduced by them? If the numbers is far from the expected or if there is large differences between different plants with similar equipment then further investigation is recommended.

2.1.2 Methods

When the energy consumption is not measured, ways to calculate it must be found. How this can be done depends on the circumstances.

2.1.2.1 Run-time and rated power

A simple way to calculate energy consumption is to use the run-time and rated power of the load. This assumes that the run-time and rated power is known or can be estimated. The calculations are done according to Equation 2.1

$$E = p_R \cdot t \tag{2.1}$$

where E is the consumed energy, p_R is rated power and t is the run-time of the load. Calculations of this kind made at Klagshamn WWTP in comparison with energy meters showed that the measured values are, in general, equivalent to about 80 % of the calculated value. This is reasonable because most motors are not run at their full rated power, due to the equipment being dimensioned for higher loads during influent flow rate peaks. Based on these results all values obtained by this kind of calculations, in this project, are multiplied by 0.8. This implicates that most motors are not run at full load all the time.

2.1.2.2 Elevation

When wastewater is lifted it is often done by large, speed controlled pumps. The speed control makes the use of run-times for calculating the energy consumption uncertain, as the load is not run at rated power most of the time. In such cases, one way to estimate the energy consumption is to calculate the energy needed to lift the wastewater. To perform this calculation the pump efficiency and the elevation height needs to be known. First the energy needed to lift one cubic meter is calculated by using Equation 2.2:

$$E = \frac{h \cdot \rho_{water} \cdot V \cdot g}{\eta} \tag{2.2}$$

where E is the energy used, h is the elevation height, ρ_{water} is the density of wastewater, V the volume, η the pump efficiency, set to 60%, and g the gravitational constant, 9.82 m/s^2. The value obtained is then multiplied with the flow in cubic meters to get the total energy consumption.

2.1.2.3 Hazen-Williams formula

The energy used to transport a certain amount of wastewater or sludge a certain distance can be calculated by combining the method in the previous section with the Hazen-Williams formula. The Hazen-Williams formula is used to transform the friction loss from transport in a pipe to an elevation height equivalent. Equation 2.3 shows the Hazen-Williams formula:

$$h = 6.05 \frac{L}{D^{4.87}} \cdot \left(\frac{Q}{C}\right)^{1.85} \tag{2.3}$$

Where h is the head loss in metres, L is the length of the pipe in metres, D is the pipe's diameter in millimetres, Q is the flow in litres/minute and C the Hazen-Williams C-factor which is a value of the friction constant for the pipe, (Water Environment Federation, 1997).

The result from the Hazen-Williams formula can then be used together with the calculations in Section 2.1.2.2 to get an estimate of the energy consumption.

2.1.2.4 Assuming similarity

When no other ways can be found, results from similar processes can be used to make estimates of energy consumption. If values can be obtained for the same type of process at the same WWTP, differences in wastewater quality can be disregarded. Otherwise this is something that must be taken into consideration as a source of error. In literature on wastewater management, typical values of the consumption of different types of equipment and processes can be found.

2.1.3 Sjölunda WWTP

At Sjölunda WWTP there are several power meters. From a process stage perspective their placement is a bit awkward, since they are not placed in accordance with the processes. Where there are no measurements the results will be based on calculations with run-time estimates and rated power where this is possible, and otherwise the result will be estimated by other theoretical calculations.

2.1.4 Klagshamn WWTP

At Klagshamn there are run-time measurements for all loads. The ranking will, with a few exception, be based on these measurements together with the corresponding rated power. For some large speed controlled pumps the calculations will be based on elevation heights instead.

2.2 Energy conservation plan

When making the energy conservation plan, the largest process steps that together represent 80 % of the total electrical energy consumption will be picked out. These selected processes will then be evaluated briefly to show where future work should be concentrated. One saving plan will be derived for each WWTP. A more detailed analysis will be performed for one process to show an example of how future studies can be done.

2.2.1 Work flow

The most important thing when designing an energy conservation plan is to decide where the main savings are likely to be achieved. As stated above the processes that together represent 80 % of the total consumption will be picked out. This will be done separately for Sjölunda and Klagshamn WWTP.

The next step is to look briefly at each of the chosen processes to derive the saving potential, based on size and type of the process.

The last thing to do on the conservation plans is to rank the processes from their saving potential.

As mentioned, above a case study will be performed for one of the process steps. Here each group of consumers included in the process will be evaluated to see if any savings are likely to achieve. Type of objects, control and dimensioning will be taken into consideration. Typical values from wastewater literature will be used to appraise the efficiency of the installed object.

2.3 Performance indicators

The third and last part of this master thesis is a section about performance indicators. The use of performance indicators in an energy conservation context will be discussed as well as methods for constructing such indicators.

Some examples of performance indicators, based on values from Sjölunda and Klagshamn WWTPs, will be developed to illustrate the usefulness of performance indicators.

3 Introduction to wastewater treatment

Both life itself and society as it is today are dependent on water for their mere existence. The lack of clean, drinkable water in many countries claims millions of lives every year, not only by dehydration but by diseases and epidemics directly related to the shortage of water. In most applications the water is purified before it is used, to protect people and equipment. When the water is used by society and its functions, it becomes contaminated. Water affected by anthropogenic influence is called wastewater. It is of grave importance that the wastewater is treated before it is returned to the environment.

This chapter is meant to be an introduction to wastewater treatment for those not familiar with the subject. This chapter should not be considered a complete description of the available methods for wastewater treatment, but instead give insight in the basic treatment processes and ideas. Readers that are already familiar with the means of wastewater treatment may very well skip this chapter.

3.1 Composition of wastewater

Water affected by human activity is called wastewater. Most commonly the term wastewater refers to water used by the community. Roughly it is a combination of industrial wastewater, domestic wastewater and groundwater leaking into the pipes. With a combined drainage system it also contains storm water. The exact composition of wastewater varies from region to region, from season to season, from day to day and from minute to minute. It depends on a large range of different factors as the time of the day, the number of industries connected to the wastewater system, the weather etc. (Kemira, 2003).

More specifically, municipal wastewater may contain (Kemira, 2003):

- Suspended solids
- Oxidizable substances
- Bacteria
- Nutrients
- Virus
- Parasite eggs
- Heavy metals
- Toxins

The contents of wastewater can be classified in a number of different ways, viewed from different angles. For example, they can be seen from a physical, chemical or biological point of view (Kommunförbundet, 1996).

3.1.1 Physical composition

From a physical point of view the contents of wastewater can be classified with respect to the size of the particles. Particles that are less than 0.1 μm are classified as solutions, particles between 0.1 and 1.0 μm as colloidal solutions, particles between 1 and 100 μm as suspended matter and particles greater than 100 μm as settleable suspended solids (Kemira, 2003).

The wastewater can also be described by its colour, temperature and smell. A measurement of the total amount of pollutants in the wastewater can be determined by evaporation of a sample of a certain volume (Kommunförbundet, 1996).

3.1.2 Chemical composition

From a chemical point of view the pollutants in the wastewater are divided into organic and inorganic particles, where organic particles are everything that is based on hydrocarbon. There are a number of different ways to define the amount of organic matter in wastewater, such as Biochemical Oxygen Demand (BOD_7), Chemical Oxygen Demand

(COD), Volatile Solids (VS), Total Solids (TS) and Total Organic Carbon (TOC). All of the above methods involve oxidizing the organic material. For BOD_7 micro organisms are used for the oxidizing and for COD a chemical oxidizer is used. For TS the dry substance of a sample are weighed, burned and weighed again to determine the amount of combustible substances. For TOC the sample is oxidized and the quantity of carbon dioxide formed is measured (Kommunförbundet, 1996).

Nutrients dominate as non-organic material in wastewater with ammonium and phosphate as the most common. The most common ions in wastewater are sodium, potassium, calcium, magnesium, ammonium, chloride, sulphate, phosphate and hydrogencarbonate (Kommunförbundet, 1996).

Phosphorus and nitrogen are the main contributors to eutrophication. In wastewater they have a unique position in that they exist in both organic and inorganic forms. Apart from the organic forms phosphorus exists as polyphosphate and orthophosphate and nitrogen as ammonium, nitrite and nitrate (Kemira, 2003).

3.1.3 Biological composition

The content of different micro organisms is evaluated when the wastewater is classified from a biological angle. The micro organisms are divided into pathogenic and non-pathogenic organisms. The pathogenic organisms are the more interesting in this case since they represent a potential health threat. They are further classified as parasitic worm eggs, bacteria and viruses. The quantity of micro organisms in municipal wastewater vary but the order of magnitude are ten billions per millilitre. The mere variety of possibilities makes it impossible to determine the exact content of pathogenic organisms. Focus lies on the micro organisms that commonly exist in human faeces (Kommunförbundet, 1996).

3.2 Importance of wastewater treatment

Wastewater treatment is an absolute necessity in today's society. The growing water consumption would be a serious threat to all effluent recipients if the wastewater was not treated before returned to the environment. Apart from the environmental impacts it is also a question of public health.

3.2.1 Environmental consequences

The list of environmental consequences of untreated wastewater is long. Apart from odours, discolouring and effects of releasing pathogenic micro organisms into oceans, lakes and watercourses, saprotrophication and eutrophication are two major environmental issues.

Saprotrophication occurs when there is an overload of organic material. Micro organisms consume the organic material during oxygen consumption leading to a decrease in dissolved oxygen concentration (Kemira, 2003). This decrease can lead to damages on biological life and, if aggravated, to fish kills (Kommunförbundet, 1996).

Eutrophication occurs when a surplus of nutrients is added to waters and watercourses. The abundance of nutrients, especially phosphorus and nitrogen, leads to an increased growth of organic substances with algal blooms as a consequence. Some algae produce toxins with great impact on the environment as a result. Another result of eutrophication is an increased quantity of organic substance which leads to saprotrophication as described above (Kemira, 2003).

3.3 Wastewater treatment processes

The aim is to remove all substances that can be a hazard to the recipient, including suspended solids, organic material, phosphorus, nitrogen etc. Many of the treatment processes replicate cleaning processes in nature. Below is a description of wastewater and sludge treatment methods at modern wastewater treatment plants. The treatment process can be divided in mechanical, biological and chemical treatment.

3.3.1 Mechanical treatment

The first part of the wastewater treatment is the mechanical treatment which aims to remove suspended particles and macro-solids, such as sanitary towels, condoms, rags etc, to protect the equipment in the following treatment steps from being damaged or clogged. Usually there are three mechanical treatment steps starting with separation of particles bigger than 2-3 mm by the aid of screens, followed by sand and grit removal. The last mechanical process is called primary sedimentation (Kemira, 2003).

In the sand and grit removal process the wastewater is aerated to give the wastewater a flow velocity at which sand and other heavy particles sink while lighter particles stay suspended in the wastewater. There are other methods used in sand catchers that do not require aeration, but instead use a centrifuge or filters to remove the sand and other heavy particles while still letting the lighter ones pass through (Kommunförbundet, 1996).

Figure 3.1 Primary sedimentation basin

In the primary sedimentation wastewater slowly passes through large basins, as the one in Figure 3.1, while suspended material is allowed to sink to the basin floor. About one third of the organic material in the wastewater is removed in this step (Kemira, 2003).

Flotation, which is the opposite of sedimentation, is another type of mechanical treatment. Part of the outgoing wastewater from the process is recirculated and oversaturated with air at 5-6 times the atmospheric pressure. When the pressurized wastewater is released back into the basin at the inlet, small bubbles form in the wastewater stream. Low density particles attach to these small bubbles and the flocs rise to the surface where they are scraped of. Flotation is often used together with chemical treatment to separate flocs of precipitated material.

Another mechanical treatment process is filters to remove the unwanted materials in the wastewater stream, and there are numerous sizes, materials, and flow directions depending on what the filter is supposed to catch.

3.3.2 Biological treatment

Biological treatment has two main objectives: To remove organic matter and to remove nitrogen. There are three different types of biological processes used in wastewater treatment: anaerobic, aerobic and anoxic. In an anaerobic process the reaction takes place in an oxygen free environment. An aerobic reaction uses the oxygen dissolved in the wastewater, and the anoxic reaction that takes place in waste water treatment releases nitrate and oxygen, where the later is used by the bacteria in the process (Kemira, 2003).

Figure 3.2 Activated sludge process

3.3.2.1 Activated sludge

The activated sludge process is an aerobic biological treatment process where sludge with high concentration is mixed with the incoming wastewater in aerated tanks, see Figure 3.2. Basically what happens is that micro organisms consume the organic matter and generate biomass. The process is complicated, with many sub processes. The added and generated sludge are separated from the wastewater in sedimentation tanks. The sludge concentration in the activated sludge line is to be held constant which is done by returning most of the sludge to the inlet while the rest is treated in the sludge treatment process described later on. Depending on the configuration of the activated sludge process, it can be used for nitrification as well. Nitrification is a process where ammonium is transformed to nitrate and it is the first step in removing nitrogen from the wastewater.

Figure 3.3 Trickling filters

3.3.2.2 Trickling filters

Another aerobic biological treatment method is trickling filters. The object of the process is nitrification and/or reduction of organic matter. It can be used instead of performing nitrification in the activated sludge step or as a complement to an overloaded activated sludge process. The filters consist of a bed of filter material with high surface area and good air circulation. Such filter media can be macadam, lava stone or plastic. The wastewater is spread onto the filter bed by rotating, perforated arms, as shown in Figure 3.3 above. When the wastewater trickles through the bed a biological film of micro organisms is formed. These micro organisms then live on the organic material in the wastewater. If the oxygen supply is unlimited the efficiency of the filters is decided by the contact surface between wastewater and filter media (Kemira, 2003).

3.3.2.3 Denitrification with suspended carriers

The second step of the nitrogen removal is called denitrification and transforms nitrate to nitrogen gas. The transformation is performed by anoxic bacteria. One example of a denitrification process is denitrification with suspended carriers. As the trickling filters this process used a biofilm. Here the biofilm grows on small plastic pieces with a large specific area, as shown in Figure 3.4, that are kept suspended in the wastewater (Kemira 2003).

Figure 3.4 Plastic carrier material

3.3.3 Chemical treatment

Chemical treatment can be applied in different steps of the treatment process and mostly aims to remove phosphorus. The main principle for chemical wastewater treatment is that a chemical substance is added to the wastewater to cause the substance that should be removed to precipitate so that it can be separated mechanically (Kemira, 2003).

3.3.4 Phosphorus removal

Phosphorus can be removed by both chemical and biological treatment processes. In chemical phosphorus removal lime or salts of iron or aluminium are added to the wastewater and the metal ions react with hydrogen phosphate forming chemical sludge. For example, ferric chloride can be used. The following reaction then takes place:

Ferriphosphate precipitation

$$Fe^{3+} + HPO_4^{2-} \rightarrow FePO_4 + H^+$$

The precipitation forms flocs that are separated from the wastewater by sedimentation, filtering or flotation. Similar reactions take place when other chemicals are used (Kommunförbundet, 1996).

Biological phosphorus removal is a process that is alternating aerobic and anaerobic. Bacteria, called polyphosphate accumulating organisms, are stressed, by the alternating aerobic and anaerobic climate, to increase their consumption of orthophosphate (Kemira, 2003).

3.4 Sludge treatment processes

Sludge is a by-product of wastewater treatment. It is accumulated in the sedimentation processes and flotation processes at a WWTP. Sludge is a combination of water and dissolved and suspended matter. The main purpose of the process is to remove the water from the sludge and to remove pathogenic organisms. Below the sludge treatment process is described.

3.4.1 Sludge thickening

To reduce the sludge volume the first step is to thicken the sludge by sedimentation or flotation. Sludge from the primary mechanical treatment is best thickened in sedimentation tanks, or gravitational thickeners, while sludge from chemical and biological treatment also can be treated by flotation (Kemira, 2003).

3.4.2 Sludge stabilizing

The organic matter in the sludge will continue to react and transform until it has been stabilized in some way. There are a number of different ways to do this.

3.4.2.1 Anaerobic digestion

The anaerobic digestion process will reduce the sludge volume drastically and will result in a sludge with considerably lower water content and less foul smell than the untreated sludge. The sludge is heated and digested by anaerobic micro organisms in a digestion chamber. The volatile solids are reduced by 40-50% and the sludge volume is reduced by 35 % (Kemira, 2003). During the digestion process the micro organisms produce methane and carbon dioxide. The gas can, after purification, be used for production of electric energy, heat or be sold as biofuel for cars etc.

3.4.2.2 Aerobic digestion

In aerobic digestion the sludge is aerated during a couple of weeks. Aerobic micro organisms digest the organic matter and produce carbon dioxide (Kemira, 2003).

3.4.2.3 Lime stabilization

Lime is a basic substance which, when added to the sludge, raises the pH-value to a level where the biological activity ceases. The lime can be added either before or after the dewatering, which is described below. Lime stabilization is a simple process but the cost of running it is high (Kemira, 2003). The process uses large quantities of lime, the sludge increases in volume taking up more space and the stabilization is not permanent, as the micro organisms will thrive again as the pH-level decreases with time.

3.4.3 Dewatering

Dewatering is usually the last step in the sludge treatment process and aims at reducing the water content of the sludge. After thickening and stabilization the sludge still contains 90-98 % water. There are a number of different methods, all mechanical, such as centrifugation and different kinds of pressing for removing the water. To improve the results of the mechanical treatment polymers are added to the sludge. Centrifugation means that the particles are separated from the water by use of centrifugal forces. Pressing means that the sludge passes through a mechanical press, which applies a force that compresses the sludge and forces the water to separate from the solids. The excess water is returned to the wastewater treatment process (Kommunförbundet, 1996).

3.4.4 Sludge disposal

The dewatered sludge has to be taken care of somehow. It contains high levels of nutrients, e.g. nitrogen and phosphorus, and can be used as an agricultural fertilizer. Unfortunately, the sludge may also contain toxins and heavy metals which lead to divided opinions about its use in farming. The sludge can also be deposited, incinerated or used as landfill.

3.4.5 Reject water treatment

At some plants the water separated in the dewatering stage is treated separately before it is returned to the process. This is normally done because the water has very high levels of ammonia, as well as a somewhat higher temperature. This makes the process more efficient than it would have been if the water had been led back into the plant. At these high concentrations, there are a large number of more efficient treatment methods that cannot be used at the much lower concentration of ammonia in the influent wastewater.

4 Processes at Sjölunda and Klagshamn WWTPs

There are many different ways to treat wastewater with regard to stages used in the plant. This greatly depends on the amount and the composition of the wastewater that reaches the WWTP as well as the limits of the allowed amount of pollutants that may be released into the recipient.

The goal of this chapter is to describe the current setup of the different stages utilised for wastewater treatment at both Sjölunda WWTP and Klagshamn WWTP in the order that they are connected, following the route of the wastewater through the WWTP, as well as an estimate of the installed power and the energy utilisation in the different stages.

4.1 Sjölunda WWTP

Sjölunda is the larger one of the two WWTPs connected to the city of Malmö's wastewater system. Sjölunda is situated on the north side of Malmö on the shore of Öresund that separates Sweden and Denmark.

The number of persons connected to Sjölunda amounted to 286 000 actual persons in 2005, which recalculated to person equivalents (p.e.), corresponds to about 284 000 p.e. based on BOD_7 load. The influent flow rate to Sjölunda was 100 000 m^3/d on an average during 2005, peaking at 257 000 m^3/d (Environmental Report Sjölunda, 2005). These numbers means that Sjöunda is a large wastewater treatment facility, one of the largest in Sweden.

It is worth noting that the excess heat in the outgoing water is utilized by heating part of Malmö through the district heating system.

Below, in Figure 4.1 is a schematic picture of the process at Sjölunda WWTP. A larger version of the same picture can be found i Appendix C.

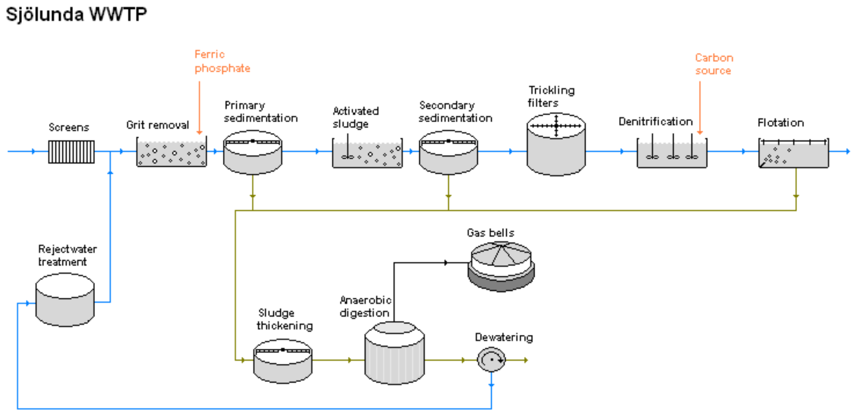


Figure 4.1 The wastewater treatment process at Sjölunda WWTP

4.1.1 Flow equalization

The flow equalisation pumps are the first stage in the wastewater treatment at Sjölunda. The wastewater arrives at the plant by means of pipes leading from pumping stations located around Malmö. The wastewater can flow into the plant on its own, but the pumps are used to reduce the peaks in the flow rate to the plant to ensure a smoother and more stable process and less regulation in the rest of the treatment stages.

4.1.2 Screens

There are four parallel screens that remove all material larger than 3mm. The height of the wastewater is measured on both sides of the screen to determine the amount of material caught, and when the difference is large enough the screen automatically moves a new clean section of the screen into position. The material that gets caught in the screen are removed and dewatered before it is transported to a waste incineration facility.

4.1.3 Grit removal and primary sedimentation

After passing through the screens, the wastewater is routed to one of the four parallel aerated sand traps where sand and heavy particles are removed. The aeration reduces the risk of the production of foul smelling hydrogen sulphide. The sand and particles are taken to the sand dewatering and cleaning where the organic material is removed. Ferric phosphate is added to the wastewater in the sand traps to increase the amount of phosphorus removed in the eight primary settling basins where the wastewater is led next. The larger organic material as well as the flocs of phosphorus created by the added ferric phosphate settle on the bottom, and is then gathered and transported to the sludge thickening stage.

4.1.4 Activated sludge

The activated sludge process at Sjölunda is composed of four parallel sections called G1-G4. G1-G3 are equal in size and flow rate, and G4, which is newly built, handle the same flow rate as G1-G3 combined.

All the basins in the four activated sludge sections use the same basic configuration with a long basin divided into three parts. In the first part of each line, the influent wastewater is mixed with sludge from the last part of the process. This section can be mixed by the use of electric mixers if the process requires it. The second part is aerated with blowers to ensure that the oxygen levels are sufficient for the micro organisms in the sludge. This is the single most energy consuming stage in the entire plant. The last part of the process is the secondary settling tank where the sludge settles to the bottom. The sludge is then collected and most of it is returned to the start of the process. As this process converts the incoming waste into more sludge than is needed, a small amount of it is removed from the cycle and pumped to the sludge treatment.

4.1.5 Trickling filters

Trickling filters are used at Sjölunda for the purpose of removing ammonia from the wastewater and converting it to nitrate. Oxygen is supplied through hatches in the bottom of the structure. The wastewater is recirculated through the filters to ensure a high load on the filters and thus an appropriate thickness of the biofilm.

4.1.6 Denitrification

After the nitrification of the ammonia in the trickling filters the wastewater is pumped to the denitrification stage. The denitrification bacteria are attached to a special plastic material that is kept suspended in the wastewater by means of mixers. As the bacteria convert nitrate into nitrogen gas they consume carbon which they acquire from an external carbon source, usually methanol or ethanol. By adding a carbon source, chemical energy is added, but as this work focuses on electrical energy this is not included in the calculations of the energy consumption. The pumps used for the carbon source addition are controlled continuously based on nitrate sensors.

4.1.7 Flotation

Before the wastewater leaves the plant it is led through a final stage for extra flock removal. The flocs are scraped of and transported to the sludge thickening basin together with the particles that are too large to rise to the surface and settle on the bottom of the basin.

4.1.8 Sludge thickening

The sludge from the primary sedimentation, the waste activated sludge and the sludge from the flotation are pumped to one of the three gravitation thickener basins. These consist of three meter deep circular basins with a scraper at the bottom that collects the sludge. In the event that the water content in the sludge after the gravitation thickening is too large, a mechanical screening press that presses more water out of the sludge is used to lower the water content in the sludge to the desired level.

4.1.9 Anaerobic digestion

The sludge from the thickeners is pumped to the digesters through a heat exchanger that preheats the incoming sludge using the heat from the already digested sludge. Inside the chambers the sludge is kept at 35°C to ensure a stable climate for the micro organisms. This process produces methane gas, which is stored in two gas bells. The gas is then used in two gas engines for electricity production or in a gas furnace to produce heat for the district heating system.

4.1.10 Dewatering

The sludge from the anaerobic digestion is stored in tanks before it is pumped to the centrifuges. In the centrifuges the sludge is mixed with polymers to increase the separation of water and solids. The resulting stabilized dewatered sludge is used in agricultural processes or for different constructional purposes, such as landfill.

4.1.11 Reject water treatment

The water that is separated from the sludge in the dewatering stage is treated in a Sequencing Batch Reactor (SBR) before it is returned to the inlet of the plant. An SBR works in sequences. First it is filled, then comes the nitrification stage, then the denitrification stage and last, the sedimentation stage. The sequence is then repeated (Kemira, 2003).

4.2 Klagshamn WWTP

Klagshamn is the smaller WWTP that services Malmö with wastewater treatment. It should be noted that it is still a medium to large WWTP by Swedish standards. It is located south of Malmö along the coast.

The number of persons connected to Klagshamn amounts to 90 000 p.e which is equivalent to an average load of 4.4 ton BOD_7/d. The average inflow is 16 300 m^3/d with a peak at 44 000 m^3/d during heavy rain (Environmental Report Klagshamn, 2005).

In Figure 4.2, a schematic picture of the process at Klagshamn WWTP is shown. A larger version of the same picture can be found i Appendix D.

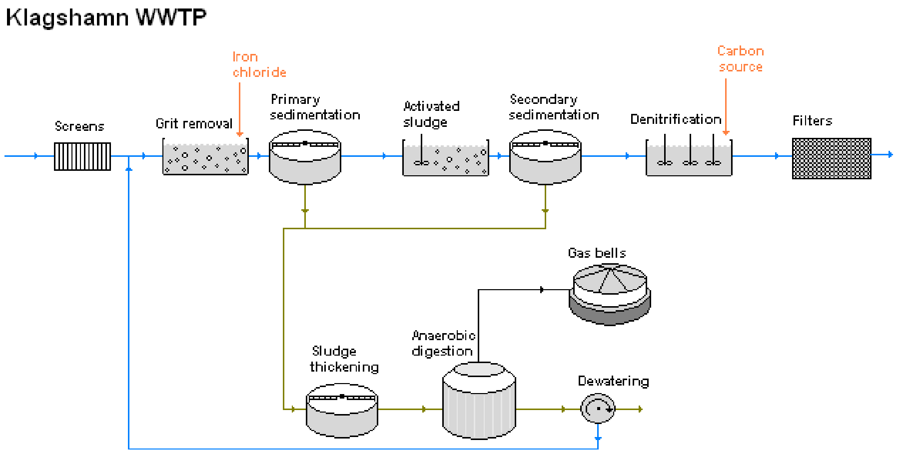


Figure 4.2 The wastewater treatment process at Klagshamn WWTP

4.2.1 Inlet pumps

The wastewater arriving at Klagshamn is lifted 9.4 m by the inlet pumps into the plant. One of the pumps run all the time and the other two can be started if the influent flow rate is large. The pipe leading the wastewater to Klagshamn is used as a temporary storage magazine to reduce peaks in the flow rate to the plant.

4.2.2 Screens

When the wastewater has entered the plant it passes through one of three screens, one with a width of 2 mm and two with a width of 3 mm. If the incoming flow rate exceeds the limit of the three screens the excess wastewater is bypassed through an extra screen. The removed waste is washed and dewatered in a screening press before it is transported to at waste incineration facility. The wastewater from the screening press is led back to the inlet of the plant.

4.2.3 Grit removal and primary sedimentation

After the screens the wastewater flows to the two aerated sand traps. The settled material is transported to the sand dewatering, and the material floating on the surface is gathered and moved to the sludge treatment. The wastewater is led to the four primary sedimentation basins and iron chloride is added to increase the amount of phosphorus that settles. The amount of iron chloride added is based on the influent flow rate to the sand traps.

4.2.4 Activated sludge

The activated sludge process consists of two parallel basins divided into nine sections each. The process is run so that, parallel with the removal of organic material through consumption by micro organisms, both nitrification and denitrification can take place depending on the amount of ammonia in the influent. All nine sections can be run as aerobic or anaerobic reactors with mixing depending on the desired amount of nitrification. A separate carbon source can be added to any of the sections.

The wastewater is pumped to the eight secondary sedimentation basins where the produced sludge from the activated sludge process is allowed to settle and is captured by chain scrapers and pumped back to the inlet of the activated sludge basins. Some of the sludge is removed from the cycle and is pumped to the sludge thickeners.

4.2.5 Denitrification

The wastewater from the secondary sedimentation is denitrified by means of bacteria growing on a suspended plastic material. To prevent the plastic material from leaving the reactor the wastewater passes a grid on its way out. The grid is kept clean by the motion of the mixers, but it can be cleaned with the use of a blower if clogging becomes a problem. It is possible to add an external carbon source if the carbon in the wastewater is insufficient for a satisfactory denitrification capacity. By doing so, chemical energy is added to the process, but this is not covered in this thesis.

4.2.6 Filters

The final stage in the wastewater treatment process consists of five parallel filters containing sand of two different sizes. The filters are cleaned by a combination of water and air at certain time intervals or when the pressure difference across the filter reaches a preset value. The wastewater used when cleaning a filter is returned to the inlet of the plant. If extra phosphorus removal is desired chemicals can be added at the filter inlet.

4.2.7 Sludge thickening

The waste sludge from the different processes in the plant is transported to one of the gravitational thickeners. These increase the amount of solids in the sludge from about 1 % to 2 %. The effluent wastewater from the thickeners are led back and mixed with the influent to the plant.

4.2.8 Anaerobic digestion

The thickened sludge is pumped to one of the two anaerobic digestion chambers. The gas produced is stored in a gas bell and then used to power two furnaces which produce heat for the sludge going into the digestion chambers and for heating of the plant’s buildings. Excess heat is sold to a nearby greenhouse.

4.2.9 Dewatering

The digested sludge is further thickened in another gravitational thickener before it is dewatered in a centrifuge. A polymer is added to increase the amount of water that is removed. The dewatered sludge is stored for later use as landfill or in agricultural soil production.

5 Energy in wastewater treatment

Wastewater treatment is a costly business with regard to energy. Swedish WWTPs consume about 0.6 TWh of electrical energy during one year, which equals about 0.4 % of the total electrical energy consumption in Sweden during the same amount of time. At a rate of 0.75 kr/kWh, 0.6 TWh, would correspond to a total cost of 450 millions SEK, if all energy was bought (Kjellén and Andersson, 2002).

In today's society it is of vital, environmental interest, as well as of economic, that the energy consumption is minimized. Energy efficiency in wastewater management is of current interest in Sweden and the Swedish Water and Wastewater Association, SWWA, has an ongoing project on this topic, called "Energiprojektet" (the Energy project). According to this project, there is, approximately, a 10 % energy saving potential in the Swedish wastewater industry (Svenskt Vatten, 2007).

5.1 Energy consumers

A common WWTP has a lot of small electric motors which together represent only a small part of the total consumption and a few big electric motors that are responsible for the rest of the consumption. The blowers, used in for instance the activated sludge process, are usually the main individual consumer at a WWTP. In Sweden in general they represent about 24 % of the total electricity consumption at WWTPs (Svenskt Vatten, 2006). The biological treatment alone stands for 50-80 % of the total electricity consumption. Below is a brief discussion of the consumers and the energy demand in the different process types used at Sjölunda and Klagshamn WWTPs.

5.1.2 Screens

The screening is a process consisting typically of small motors, at least from a wastewater treatment perspective. To avoid clogging, the screens are raked occasionally with raking devices driven by motors or operated by hand. There are also motors for washers and different transporters used to move the screenings from the screens.

5.1.3 Grit removal and primary settling

In the first part of this process where the wastewater is aerated and the sand and grit is removed, blowers are used. At Sjölunda these are small related to the ones used in the activated sludge process but they are still fairly large motors. There are scrapers in both the grit removal and the following sedimentation. These have, typically, a rated power around 1 kW, which is small in these circumstances. There are also some pumps used to transport the sludge from the sedimentation tanks to the sludge treatment. The blowers and the scrapers operate almost continuously.

5.1.4 Activated sludge

The activated sludge process represents a large part of the energy consumption. The main consumers in the process are the blowers. At Sjölunda these have a rated power ranging from 65-250 kW. Sometimes mixers are used too. There are pumps for the return activated sludge as well as scrapers for the sedimentation. Most of these components run all the time.

5.1.5 Trickling filters

The trickling filters' only consumers are the pumps used to transport the wastewater to the top where the spreading arms are located. This requires large pumps, at Sjölunda they range from 90-132 kW. This process recirculate some of the wastewater which increases the energy usage.

5.1.6 Denitrification

Denitrification with bacteria growing on suspended carriers, as used at both Sjölunda and Klagshamn WWTPs, uses mainly small mixers and pumps. The mixers run all the time. A carbon source, methanol or ethanol, has to be added to the process which adds to the cost of the process.

5.1.7 Flotation

In a flotation process quite large pumps are used to pressurize the dispersion water. Together with low energy scrapers and mixers that run all the time this makes the flotation process costly from an energy perspective.

5.1.8 Filters

Pumps are used to rinse the filters with water to prevent clogging. These pumps are the main energy consumers of the filter process.

5.1.9 Sludge thickening

Sludge thickening by gravitational thickeners uses scrapers and pumps. The scrapers typically have small rated power and pumps are dimensioned by the amount of sludge produced.

5.1.10 Anaerobic digestion

The sludge in the digesters has to be kept in motion. This can be obtained by mixers, compressors or pumps or a combination of these. At Sjölunda WWTP all three are used and at Klagshamn WWTP pumps and compressors are used. A large part of the energy used by pumps are used when preheating the incoming sludge with the excess heat from the outgoing sludge by means of heat exchangers. This increases the energy usage of the process, but it also increases the amount of gas that can be used for production of electrical energy. The net outcome of the process increase despite the seemingly increasing energy usage.

5.1.11 Dewatering

Dewatering of the sludge is done by centrifugation at both Klagshamn and Sjölunda WWTP. Apart from the centrifuges themselves, there are mixers for the storage tank, pumps and transporters. An average centrifuge at Klagshamn or Sjölunda WWTP has a rated power of about 20 kW.

5.1.12 Reject water treatment

Small pumps are used for transport and filling of the reactors. Blowers are used to aerate the wastewater and mixers for mixing it. The rated power of the blowers used for the SBR at Sjölunda WWTP range from 75 kW to 88 kW.

5.1.13 Transportation

Apart from the equipment used directly in the treatment process there are pumps used to move the wastewater into the plant, out from the plant and from one stage to another. The sizes and numbers of these pumps depend on the geographical conditions as well as the layout of the plant. At Klagshamn WWTP the wastewater has to be elevated to get into the plant. This is not needed at Sjölunda WWTP. At Sjölunda the wastewater sometimes has to be pumped out, when the effluent flow rate is high or the water level in the recipient, Öresund, is high.

5.1.14 Consumers

To clarify the magnitude of the matter a summary of the energy consumers at each WWTP is presented below in Table 5.1 for Sjölunda and Table 5.2 for Klagshamn. Values in *italic* are approximated.

Process	**Type of object**	**Quantity**	**Rated power (kW)**
Flow equalization	Pumps	3	75
Screens	Conveyor belts	12	4-7.5
	Motors	15	0.37-2.2
	Pumps	1	4.5
	Screens	4	5.5
Grit removal + prim. sed	Blowers	6	45-55
	Mixers	2	4
	Pumps	19	2.2-13
	Scrapers	10	0.75-2
Activated sludge (G1-G3)	Blowers	9	65-90
	Mixers	13	1.5-2.2
	Pumps	42	2-5.5
	Scrapers	20	1.1-3.5
(G4)	Blowers	3	200-250

	Inlet pumps	4	65-75
	Mixers	9	1.5
	Pumps	8	1.2-18.5
	Scrapers	14	1.5
Trickling filters	Pumps	5	90-132
Denitrification	Mixers	36	4
	Pumps	17	0.18-30
Flotation	Conveyors	8	4
	Mixers	68	0.37-0.55
	Pumps	18	0.34-212
	Scrapers	32	0.75
	Screws	4	0.25
Sludge thickening	Motors	1	1.5
	Press	1	1
	Pumps	7	7.5-15
	Scrapers	3	1.8
	Screws	3	0.75-1.3
Anaerobic digestion	Gas compressors	2	34
	Mixers	10	1.5-5.5
	Pumps	21	1.1-15
Dewatering	Centrifuges	3	18.5
	Conveyors	1	*1.5*
	Mixers	4	0.55-2
	Pumps	19	0.15-7-5
	Screws	9	5.5-30

Reject water treatment	Blowers	3	75-88
	Mixer	1	*4*
	Pumps	9	0.37-2.5

Table 5.1 Energy consumers at Sjölunda WWTP

Process	**Type of object**	**Quantity**	**Rated power (kW)**
Inlet	Pumps	3	112.6-160
Screens	Conveyors	5	1.1-8.8
	Presses	1	3
	Pumps	1	3
	Screens	3	3
Grit removal + prim. sed	Mixers	4	0.18-0.37
	Pumps	14	0.09-15
	Scrapers	16	1.3-3.88
Activated sludge	Blowers	5	78/52
	Mixers	10	1.5
	Pumps	11	5.5-11
	Scrapers	8	0.18
	Drums	2	1.1-2
Denitrification	Blowers	2	36-45
	Mixers	6	5.6
	Pumps	10	0.18-22
Filters	Blowers	1	51
	Pumps	8	0.37-37
Sludge thickening	Mixers	2	0.26-1.1
	Pumps	2	11

Anaerobic digestion	Fans	1	1.3
	Compressors	3	11-42
	Pumps	4	11
Dewatering	Centrifuges	2	22.5
	Conveyors	9	1.1-18.5
	Mixers	1	1.5
	Pumps	5	1.1-4
	Screws	1	0.25

Table 5.2 Energy consumers at Klagshamn WWTP

6 Energy usage inventory

Good knowledge about the existing process is the key to a more energy efficient management, so the first step in making a plan for energy conservation is to evaluate the current process. This chapter describes the process of evaluating the treatment processes at Sjölunda and Klagshamn WWTP. The plants will be described separately in different sections below. This inventory does not claim to be a total energy balance, since heat will be excluded. This is merely an attempt to rank the energy consumers and divide the electricity bill between the different stages of the treatment process. Before starting the actual process inventory lists of energy consumers were put together. These can be found in Appendix A and B. As mentioned before the treatment processes will be evaluated in process stages, as defined in the list below.

- Inlet
- Flow equalisation
- Screens
- Grit removal and primary sedimentation
- Activated sludge
- Trickling filters
- Denitrification
- Flotation
- Filtering
- Sludge thickening
- Anaerobic digestion
- Dewatering
- Reject water treatment

Inlet and Filtering apply only at Klagshamn WWTP while Flow equalisation, Trickling filters, Flotation and Reject water treatment exist only at Sjölunda WWTP.

6.1 Sjölunda WWTP

The first step in constructing the inventory was to investigate how the power meters corresponded to these processes. Five out of eleven stages are measured directly; these are listed below in Table 6.1. The total energy consumption of Sjölunda WWTP 2005 was 18 400 MWh.

Process	% of total electrical energy usage	Electrical energy usage (MWh)
Flow equalisation	5	931
Trickling filters	17	3080
Anaerobe digestion	6	1048
Sludge dewatering	4	766
Reject water treat.	3	464

Table 6.1 Percentage and absolute energy usage at Sjölunda WWTP

This leaves the following stages to be evaluated by other means;

- Screens
- Grit removal and primary sedimentation
- Activated sludge
- Denitrification
- Flotation
- Sludge thickening

Below the evaluation of these stages will be carried out separately. Different methods will be used. In some cases, the starting point will be the process stage itself and in other cases a specific power meter will serve as the starting point.

6.1.1 Power meter E124

Power meter E124 measures the combined electrical energy consumption of three of the eleven stages stated above. These are the screens, the grit removal and primary sedimentation and the sludge thickening. To split the measured value among the process stages, an estimate of each stage's consumption is done below.

6.1.1.1 Screens

The best way to get an estimate of the screens' consumption was via the run-times. As mentioned before, there are no standard run-time measurements at Sjölunda. The run-times had to be estimated in some way. Fortunately, the screening process is undergoing some changes and is under evaluation at the moment. The screening process at Sjölunda WWTP has two parallel lines. The equipment in one of the lines has been exchanged with new equipment recently. At the newly renovated side the run-times have been measured for about a month. The calculations to estimate the total consumption of the screens are based on these run-times. The older equipment in the other line is assumed to use the same amount of energy as the newer one. This may be an uncertain assumption but no run-time estimates were obtainable for the non-renovated side. Considering that the new equipment are of the same type as the former and that the amount of wastewater treated is the same, this is probably still a valid way of calculating the energy consumption.

6.1.1.2 Grit removal and primary sedimentation

In the grit removal and primary sedimentation stage no run-times are measured at all. The calculations presented are based on run-time estimates made by the plant staff.

6.1.1.3 Sludge thickening

The last process measured by power meter E124 is the sludge thickening. As in the grit removal and primary sedimentation case above, there are no run-time measurements available for calculating the energy consumption. Again the calculation had to be based on run-time estimates by the plant staff.

6.1.1.4 Conclusions

If the values obtained by the estimations described above are summated, the total calculated energy consumption exceeds the measured consumption. Assuming that the values calculated for each process represent the true proportions, these were used to estimate the contribution of each process stage to the total measured energy consumption. This assumption led to the results presented in Table 6.2. When considering the validity of the assumptions made in these calculations the fact that the three process stages together represent only a small fraction of the plant's total energy consumption should be taken into account.

Process	**% of total electrical energy usage**	**Electrical energy usage (MWh)**
Screens	0.2	38.5
Grit removal	3	635
Sludge thickening	2	289

Table 6.2 Percentage of total energy used by processes connected to power meter E124

6.1.2 Activated sludge

The activated sludge process at Sjölunda has been described earlier as consisting of four different lines, where three are measured individually and the fourth is measured together with other process stages. The line that lack individual power monitoring is divided on two different power meters. The secondary sedimentation is measured together with the flotation and the activated sludge process itself is measured together with the denitrification and the reject water nitrification.

To separate the energy consumption of the secondary sedimentation from the energy consumption of the flotation process, the energy consumption of one of the processes would have to be calculated. The sedimentation process has got few consumers and is far less complicated than the flotation process. There are only two groups of energy consumers in the sedimentation; the scrapers and the surplus activated sludge pumps. Run-time estimates were used once again, to calculate the energy consumption of the scrapers. For the pumps no run-time estimates were obtainable. Instead Hazen-Williams formula, described in Chapter 2, was used.

To use estimated run-times to obtain values for the activated sludge process' main energy consumers; the blowers, would be faulty since they are speed controlled. To estimate the energy used by the blowers the energy consumed was assumed to be proportional to the wastewater flow. Then values obtained from the three other activated sludge lines could be used. In those three lines the energy consumed by the blowers is measured separately. The danger in using such an assumption in this case is that the equipment in the fourth, unmeasured, line is newer, and hopefully, more energy efficient.

Figure 6.1 Screw pumps

The wastewater has to be elevated to reach the inlet of the fourth activated sludge line. This is done by large screwpumps, as seen in Figure 6.1. The screws are on-off controlled, but since the amount of wastewater pumped by a screw pump is determined by the water level in the collection sump of the pump, the run-times could not be used. Instead the energy needed to lift the wastewater the required distance was calculated. The screws where assumed to have an efficiency of 0.6. Identical calculations were used to estimate the energy needed for transporting the return activated sludge from the sedimentation back to the process, which is done by the same type of screw.

After the calculations described above the only thing left to estimate is the energy used by the scrapers and mixers. This was done by using run-time estimates. Detailed calculations can be found in Appendix E.

6.1.2.1 Conclusions

With the energy consumption of the unmeasured activated sludge line calculated, what remained to do was to summarize the energy consumption of the four lines. These calculations, together with the power meters, results in values for both the flotation process and the denitrification. The results are presented in Table 6.3 below. It should be noted that the compressors that are included in the energy consumption of the flotation process also serves the whole WWTP, except the workshop, with compressed air that drives the valves and instruments. This is of course a source of error, and it is at the present time not possible to determine how much of the energy used by the compressors are used for dispersion water compression and how much is used for production of valve and instrument air.

Process	**% of total electrical energy usage**	**Electrical energy usage (MWh)**
Activated sludge	30	5340
Flotation	17	3120
Denitrification	6	1150

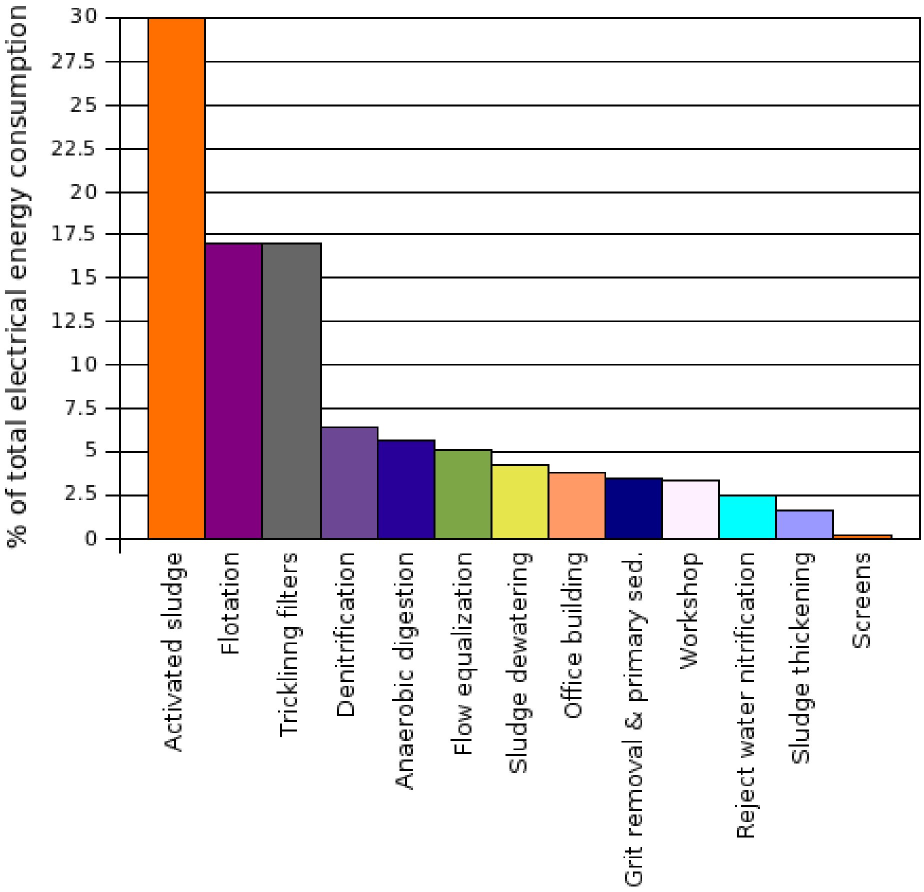
Table 6.3 Percentage of energy usage at Sjölunda WWTP

6.1.3 Process ranking

The calculations and measurements described in the previous sections can be used to show how the energy consumption is distributed at the plant. The results can be viewed in Table 6.4 and Figure 6.2 below.

Process	**% of total electrical energy usage**	**Electrical energy usage (MWh)**
Activated sludge	30	5340
Flotation	17	3120
Trickling filters	17	3080
Denitrification	6.4	1150
Anaerobic digestion	5.7	1048
Flow equalisation	5.1	931
Sludge dewatering	4.2	766
Office building	3.8	704
Grit removal	3.5	635
Workshop	3.4	623
Reject water treat.	2.5	464
Sludge thickening	1.6	289
Screens	0.2	38.5

Table 6.4 Process ranking at Sjölunda WWTP



The marked process stages represent the main contributors adding up to roughly 80 % of the total energy consumption. These processes will be further evaluated in this report.

6.1.4 Elevations

The wastewater is elevated at two points during the treatment at Sjölunda WWTP. It can be a matter of discussion whether to view these as a separate category or as done above, together with the processes where the elevations occur. The wastewater is elevated first at the inlet to one of the activated sludge processes and then again at the denitrification inlet. Below in Table 6.5 the processes and how large percentage of the total energy consumption they represent are presented, this time with the elevations as an individual post.

Process	**% of total electrical energy usage**	**Electrical energy usage (MWh)**
Activated sludge	27	4990
Flotation	17	3120
Trickling filters	17	3080
Anaerobic digestion	5.7	1048
Flow equalisation	5.1	931
Elevations	5.0	905
Sludge dewatering	4.2	766
Denitrification	4.0	742
Office building	3.8	704
Grit removal	3.5	635
Workshop	3.4	623
Reject water treat.	2.5	464
Sludge thickening	1.6	289
Screens	0.2	38.5

Table 6.5 Process ranking at Sjölunda WWTP, elevation separated

As before, the darker rows in the table marks the processes that together represent 80 % of the total energy consumption. Below, in Figure 6.3, the results of Table 6.5 can be viewed again.

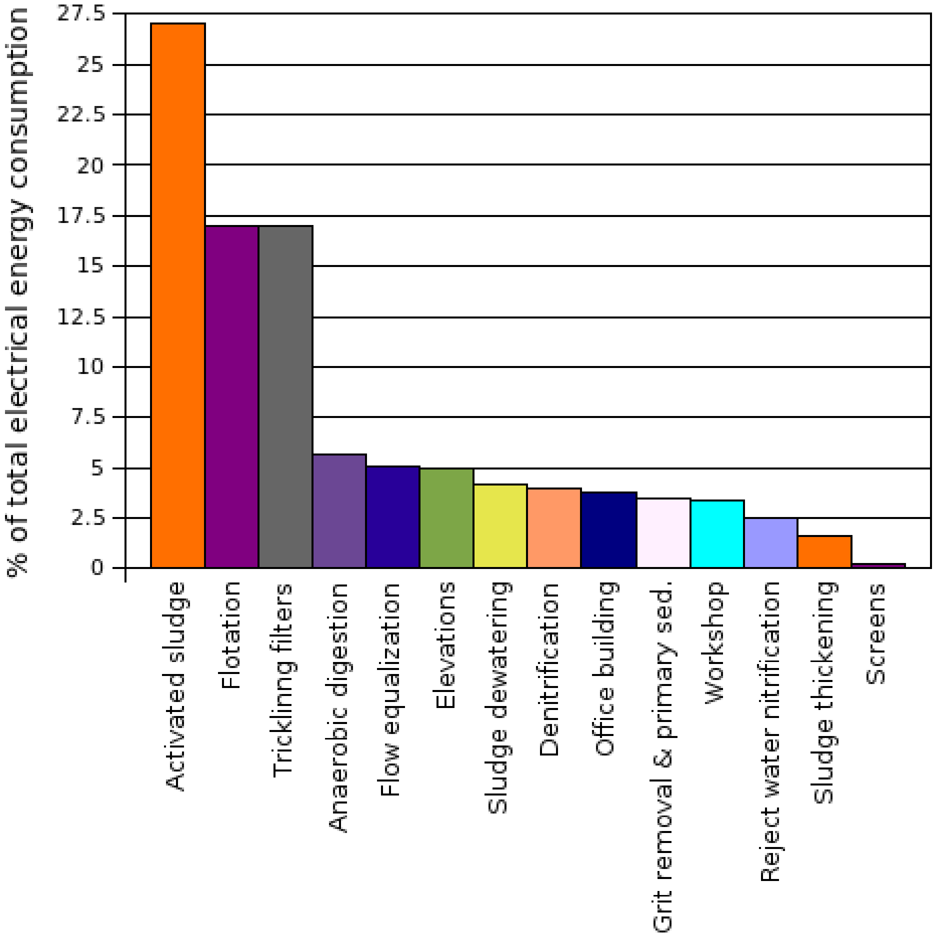


Figure 6.3 Process ranking at Sjölunda WWTP, elevation separated

Designing for elevations is a part of the design process when planning and installing a new process. Therefore the results from Section 6.1.3 will be used for deciding which processes to evaluate further for the energy conservation plan.

6.2 Klagshamn WWTP

The energy inventory for Klagshamn WWTP was easier to create than for Sjölunda WWTP since the control software at Klagshamn measures the run-times of every single object in the process. Some of the speed controlled objects had to be further evaluated. The process stages where run-time estimates could be used for the over all calculations are shown in Table 6.6 below. The total electrical energy consumption 2005 was 2130 MWh.

Process	**% of total electrical energy usage**	**Electrical energy usage (MWh)**
Screens	0.44	9
Filters	1.7	36
Sludge thickening	1.2	25
Anaerobic digestion	12	248
Sludge dewatering	6.8	145
Miscellaneous	12	250

Table 6.6 Percentage of energy usage at Klagshamn WWTP

6.2.1 Inlet

Two of the three inlet pumps are speed controlled. To calculate the energy consumed by the inlet pumps the energy needed to lift the wastewater the required distance was calculated. The screw pumps were assumed to have an efficiency of 0.6. The consumption of the inlet pumps can be seen in Table 6.7.

Process	**% of total electrical energy usage**	**Electrical energy usage (MWh)**
Inlet	15	318

Table 6.7 Percentage of energy usage at Klagshamn WWTP

6.2.2 Denitrification

The wastewater is elevated to reach the denitrification inlet. The pumps are speed controlled and the energy consumption was calculated as for the inlet pumps above. The energy used by the mixers in the denitrification process are calculated based on their run-time and rated power. The result is shown in Table 6.8 below.

Process	**% of total electrical energy usage**	**Electrical energy usage (MWh)**
Denitrification	11	227

Table 6.8 Percentage of energy usage at Klagshamn WWTP

6.2.3 Blowers

The blowers at Klagshamn WWTP are shared by the grit removal and the activated sludge process. The energy consumption of the blowers has been divided based on the air flow to each of the processes. The energy consumption of the remaining loads, scrapers, pumps and mixers, in the two processes are calculated with the help of their run-times. This gives the energy consumptions shown in Table 6.9.

Process	**% of total electrical energy usage**	**Electrical energy usage (MWh)**
Grit removal	6.1	131
Activated sludge	35	739

Table 6.9 Percentage of energy usage at Klagshamn WWTP

6.2.4 Consumer ranking

The calculations and measurements described in the previous sections can be used to show how the energy consumption is distributed throughout the plant. The results can be viewed in Table 6.10 and Figure 6.4 below.

Process	**% of total electrical energy usage**	**Electrical energy usage (MWh)**
Activated sludge	35	739
Inlet	15	318
Anaerobic digestion	12	248
Miscellaneous	12	250
Denitrification	11	227
Sludge dewatering	6.8	145
Grit removal	6.1	131
Filters	1.7	36
Sludge thickening	1.2	25
Screens	0.44	9

Table 6.10 Process ranking at Klagshamn WWTP

The marked processes represent the main contributors adding up to roughly 80 % of the total energy consumption. The post “Miscellaneous” was omitted since it does not represent a process but rather a group of individual consumers, including the compressors for compressed air used both in the process for adjusting valves etc. and in the workshop. These represent, by far, the major part of this post. Other objects under “Miscellaneous” is ventilation and gas furnaces for the biogas.

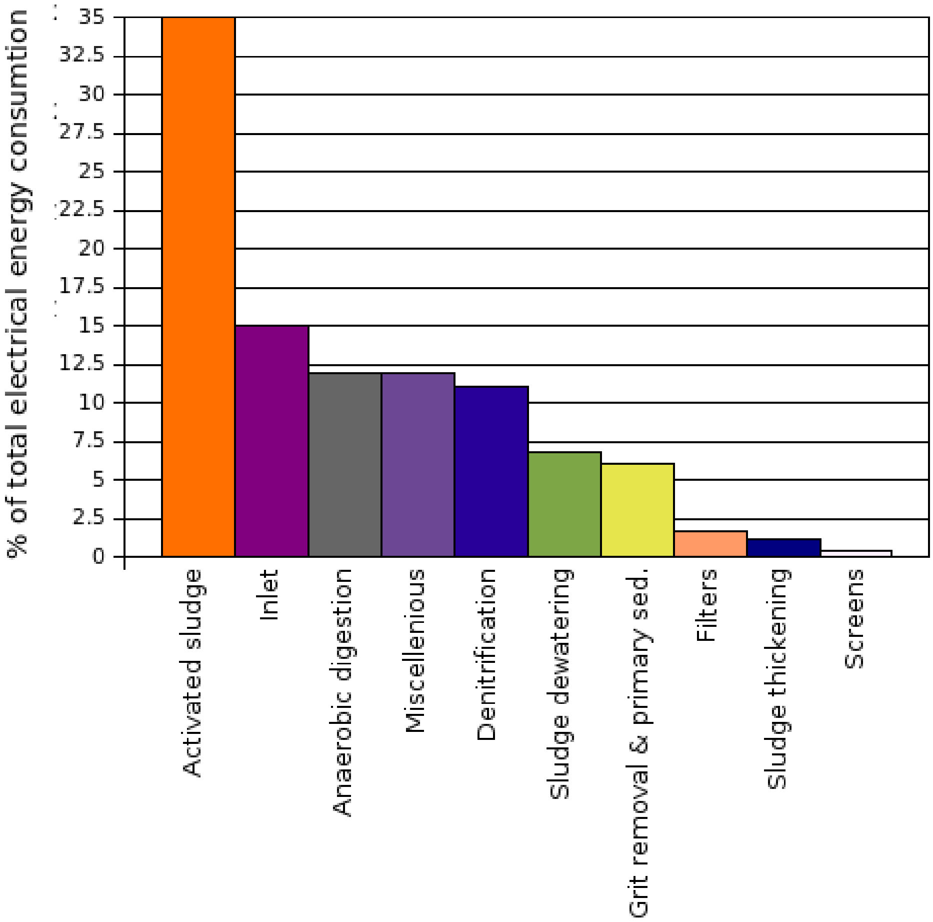


Figure 6.4 Process ranking at Klagshamn WWTP

6.3 Potential errors and uncertainty

The calculations used to construct the consumption ranking above are in many cases based on estimates made by the plant staff, since nothing else were obtainable. This implies a risk for significant errors. The method of calculating the energy consumption as 80 % of the run-time multiplied with the rated power is as well a source of errors. Calculating the energy for lifting the wastewater like it has been done above is uncertain too.

All of the above introduce uncertainty to the rankings above. Since no more information was available this is the best that could be done within the limitations of this work. For these rankings to be useful for constructing an energy conservation plan, no higher accuracy is needed.

One way to determining the correctness of the obtained rankings is to compare them with each other and with average values. For example the aeration, which is a large post at every WWTP, represent on average, 24 % of the total electrical energy consumption at a Swedish WWTP, according to a report from SWWA (Svenskt Vatten, 2007). At Sjölunda the aeration represent 24 %, which seem to fit very well. The same value is 26 % for Klagshamn and so there as well, the calculations seem plausible.

7 Energy conservation plans

This chapter discusses how to make the chosen process steps more energy efficient. The main process steps that together consume 80 % of the total electrical energy at Sjölunda and Klagshamn WWTP, respectively, will be taken into consideration. The aim of this chapter is to produce energy conservation plans for Sjölunda and Klagshamn WWTPs.

7.1 Sjölunda WWTP

At Sjölunda WWTP six processes together represent about 80 % of the total electrical energy consumption. These processes will be discussed separately in the order mentioned below in Table 7.1. It is recommended to examine the major consumer first when determining if it is possible to conserve energy, as the largest consumers have the highest saving potential, both in raw energy as well as in economical terms. It is, however, important not to overlook the smaller objects in the different processes.

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Process	**% of total electrical energy usage**	**Electrical energy usage (kWh)**
Activated sludge	30	5340
Flotation	17	3120
Trickling filters	17	3080
Denitrification	6.4	1150
Anaerobic digestion	5.7	1048
Flow equalisation	5.1	931

Table 7.1 Top six energy consuming processes at Sjölunda WWTP

The activated sludge process at Sjölunda WWTP will serve as a case study and will be discussed in depth to show how to reason and what to consider when evaluating a wastewater treatment process from an energy conservation perspective.

An important aspect in the pursue of a more energy efficient operation is not to forget to regularly clean equipment and check for worn parts. A soiled air filter to a blower, a worn out impeller in a pump or diffusers in the aeration equipment covered with micro organisms lowers the efficiency by a noticeable amount. Therefore the need for routine maintenance at regular intervals are important (Water Environment Federation, 1997).

7.1.1 Activated sludge – case study

The activated sludge process at a WWTP is often the most energy consuming process, making it a good candidate for energy conservation studies. The component that uses the most energy is usually the blowers which provide oxygen for the micro organisms in the sludge. The other consumers in the process also use a substantial amount of the energy consumed at the WWTP, but the saving potential is probably less. An approximate ranking of the individual energy consumers in the activated sludge process can be seen below in Table 7.2.

Object	**% of total electrical energy consumption in the activated sludge process**
Blowers	70
Return sludge pumps	10
Inlet pumps (G4)	8.7
Scrapers	8.0
Mixers	3.3

Table 7.2 Ranking of individual consumers in the activated sludge process at Sjölunda WWTP

7.1.1.1 Blowers and aeration

The blowers are usually one of the largest individual energy consumer at a WWTP with an activated sludge process. Their job is, as mentioned before, to supply oxygen to the micro organisms in the activated sludge and, in some configurations, to provide mixing to prevent settling of the mixed liquor suspended solids.

There are two main types of blowers or compressors; the piston compressor and the centrifugal blower or turbo compressor. The piston compressor efficiency lies in the 50-65 % range including the efficiency of the motor and the frequency modulator. The air flow can be regulated down to 20-30 % of the nominal flow without problems. At air volumes above 2000 m^3/h, the turbo compressor is a viable choice. Its efficiency can be as high as 80% at nominal load, but the air flow of a turbo compressor can only be regulated down to about 45 % of the nominal flow (Kjellén - Andersson, 2002).

When choosing what blowers to use, there are many factors to take into account. The most important factor is the amount of oxygen needed in the process. This is hard to determine, as it is affected by many factors. These include, among other things, the biological oxygen demand, the chemical oxygen demand, the nitrogenous demand, the amount of dissolved oxygen in the wastewater and the desired degree of stabilization. Setting up a model of the proposed tank layout and running simulations can greatly help when determining the oxygen demand of a process (Water Environment Federation, 1997).

When the theoretical amount of oxygen needed by the treatment process is known, the oxygen transfer efficiency (OTE) is the next thing to determine. The amount of oxygen transferred from the bubbles into the wastewater is affected by several things. A deeper tank allows the diffusers to be placed at greater depth and also increases the OTE as the hydrostatic pressure and the rise time of the bubbles increase. Both these factors increase the amount of oxygen released into the wastewater. However, the energy required for blowing air into water increases with the depth, so too large a depth should be avoided. The most common way to solve this in the design phase is to set the tank depth based on local build restrictions and then choose a diffuser with good efficiency at that specific depth. In an existing WWTP the depth of the tank is already set, and when changing the diffusers, a suitable diffuser with a high OTE for the existing depth should be used (Water Environment Federation, 1997).

The diffuser type used also affects the OTE. Different diffusers have different OTEs, and it varies with pressure and air flow. Smaller holes produce finer bubbles, but also require a higher pressure; something the rest of the aeration system must be capable of delivering. Fine-pore diffusers generally have a higher OTE than coarse-bubble diffusers, but they are more sensitive to disturbances and need more maintenance. In fine-pore diffusers the OTE also changes with the air flow. The OTE of a coarse-bubble diffuser on the other hand changes significantly less over the diffusers' allowed air flow range. Generally, a lower air flow gives higher OTE, down to the lowest allowed air flow through the diffuser. This indicates that the best setup is many diffusers, loaded at their lowest allowed air flow (Water Environment Federation, 1997).

One of the most important things that affect the OTE is the alpha factor. This is the ratio of the oxygen transfer in wastewater to that in clean water. The more fouled the wastewater is, the lower the value of alpha gets. It is therefore hard to determine alpha for a given process, as it not only changes with the load but also changes along the length of the tank as the wastewater gets cleaner further down the process. The alpha factor is most noticeable in systems with fine-pore diffusers, but it affects all systems, regardless of the diffuser type, by lowering the OTE (Water Environment Federation, 1997).

7.1.1.2 Aeration at Sjölunda WWTP

The aeration systems used in the four different activated sludge lines at Sjölunda WWTP are not identical. Two of the systems consist of one turbo compressor and two piston compressors, one of which is speed controlled. The other two systems consist of three turbo compressors each. The control system should try to make sure that the compressors that do run are running as close to their nominal load as possible. It is better to run one compressor close to its rated power than two at half their rated power, as the efficiency of both the compressor and the motor is higher closer to the nominal load. The blowers are regulated based on the pressure in the air system, which is kept at a constant level.

The amount of air needed in the aerated sections of the activated sludge tanks is closely monitored. Two of the lines are divided into five sections, with the possibility to aerate all of them. There are dissolved oxygen meters in the last three sections controlling the valves for the incoming air in their own section. The third line is divided into eight sections, and every other is equipped with an oxygen meter. The meters control the valves in the section they are placed, as well as in the section just before. The fourth line is divided into four sections, with meters in the second, third and fourth tank. The first sections in all the tanks can be run without aeration, and mixers are installed to make sure the suspended solids are kept suspended if this is the case.

There might be room for improvement in the regulation of the oxygen levels. The controllers in all the sections of the activated sludge systems are set to 2 mg/l of dissolved oxygen. This level of oxygen might not be needed throughout the length of the tank. Running simulations similar to the ones done in the master thesis about energy conservation at Himmerfjärden WWTP (Andersson – Holmberg, 2006) might give individual values for the different sections in the four lines, and thereby possibly lowering the oxygen demands of the process as a whole, or at least make sure the oxygen is used in the correct section of the system.

7.1.1.3 Choosing pumps

When choosing what pump to install, it is important to make sure that the pump is suitable for the task. The rated discharge, the system head and the piping attached to the pump must all match. If one of these parameters do not match the required value, the pump will not perform efficiently. An oversized pump will either have to be run at slower speed and thus at an inefficient operating point, or run intermittently and create an excessive flow that creates a large friction loss in the pipes. An undersized pump will struggle to deliver the necessary flow and will also run at an inefficient operating point.

7.1.1.4 Return activated sludge pumps

The return activated sludge pumps are responsible for transporting the sludge from the sedimentation tank back to the inlet of the activated sludge process. There are three centrifugal pumps for each of the three smaller activated sludge processes at Sjölunda WWTP. G4, the fourth and newest process, use one screw pump similar to the inlet pumps of the process.

The centrifugal pumps are controlled based on the influent flow rate to each of the processes. The incoming flow rate should dictate the amount of sludge that needs to be recirculated accurately enough.

The screw pump placed as return activated sludge pump in G4 is run continuously. It might be possible to shut it down when the combined influent flow rate and the return activated sludge flow rate can be pumped efficiently by one inlet pump and let one of the inlet pumps for G4 be used as a return sludge pump as well as an inlet pump. Instead of running two pumps at low efficiency, one pump at a higher efficiency would be used instead. This would not require any change in the layout of the plant, as the return activated sludge can already be lifted by the inlet pumps if the need arise. The wear and tear on the pump increases if the pump is switched on and of too frequent though, so intermittent running should be used cautiously.

7.1.1.5 Inlet pumps to G4

The three screw type inlet pumps to G4 are controlled based on the wastewater level at the input of the pump. One pump is run continuously, and if the wastewater on the input side rises above a predetermined level, another pump is started. The control strategy used tries to make sure that there is an evenly distributed usage of the three pumps by running the pumps an equal amount of time. Using screw pumps instead of centrifugal pumps have some advantages. A screw pump has an efficiency in the same range as a centrifugal pump, it is easy to control, and it is self regulating as it pumps more water if more water is available. This means that there is no need for anything else than on-off control.

The tanks for the activated sludge process G4, is placed above ground. If the tanks had been placed in the ground instead, the inlet pumps would have had a lower lift height. This would have saved energy in the long run if no other elevation would have been needed, but it is not certain that any cost reductions could have been achieved, depending on the possibilities and the cost for digging.

7.1.1.6 Scrapers

The scrapers in the different tanks are run continuously without any connection to the control system. These motors are small, but, according to calculations in this work, they represent 8% of the electrical energy used in the activated sludge process. 8 % may seem to be quite a big post, compared to other WWTPs, Klagshamn for instance. One reason for this might be that the motors use significantly less energy than indicated by the power rating due to them being connected to large gear boxes and having just a small load.

Running the scrapers intermittently will reduce the energy usage proportionally to the pause time, but the cost of connecting the motors to the control system must not be overlooked. Not running the scrapers all the time might also disturb the sludge recirculation, as the return sludge pumps might remove all the sedimented sludge before the scrapers start again. The drawbacks of intermittent operation is that starting and stopping motors increase the wear and tear on them, and the current drawn during the startup is several times larger than the current drawn when they are running.

7.1.1.7 Mixers

The mixers in the activated sludge tanks are run without interaction with the control system. Their job is to make sure that the contents of the tanks are mixed uniformly. There are typical values of the energy necessary to do this, but it depends on the geometry of the tank and the mixer. A way of reducing the consumed energy is either to shut down mixers whilst making sure that the remaining ones are capable of adequate mixing, or to run the installed ones intermittently. A combination of the two methods might also be appropriate. Intermittent operation does increase the wear and tear on the motors, as described in Section 7.1.1.6.

As the aeration system is responsible for both aerating the sludge and keeping it suspended, it might be a good idea to add mixers in the last sections of the activated sludge tanks, which the control system can then manipulate. This could help reducing the energy consumption of the process by running mixers instead of the aeration system if the oxygen demand is so low that the air flow does not keep the solids suspended. If the goal is to keep the mixed liquor suspended solids mixed, a mixer is more energy efficient than the aeration system. One must consider the cost of adding and connecting the additional mixers to the control system though, as well as estimate the change in energy consumption before initiating such a project. Another positive effect of such a modification is that the system becomes more flexible and different operating strategies becomes possible.

Another approach would be to simply let the suspended solids settle on the bottom of the tank by shutting down the aeration system in that section of the line for a short while before resuming the aeration of the tank again.

7.1.2 Flotation

The flotation process consists of 8 basins that are used in parallel. The scrapers are time- and sequence-controlled to ensure that the amount of removed sludge does not exceed the amount the sludge pumps are capable of pumping. This is good from an energy conservation perspective since the scrapers gather more sludge if the sludge has time to rise or settle properly. Running them in a sequential manner also lowers the peak energy usage in the process. The sludge pumps are controlled by the influent flow rate as well as the amount of sludge gathered and available for pumping to make sure that they do not run when not needed. An approximate ranking of the individual energy consumers in the flotation process can be seen below in Table 7.3.

Object	**% of total electrical energy usage in the flotation process**
Dispersion water pumps	62
Floating sludge pumps	20
Scrapers	11
Settled sludge pumps	7

Table 7.3 Ranking of individual consumers in the flotation process at Sjölunda WWTP

7.1.3 Trickling filters

The saving potential in the trickling filter process is not very large. The pumps are the only load in the process, they are quite new, and they are well controlled based on the amount of wastewater recirculated. This could be changed to a lower amount, reducing the energy consumption, but that increases the risk of excessive growth in the filter leading to reduced efficiency of the treatment process. Changing the recirculation ratio is difficult as it takes several days before the change in water flow rate is noticed as a change in thickness of the biofilm, making it difficult to know if the result is a long term stable condition.

7.1.4 Denitrification

In the denitrification process the mixers are used to keep the carriers suspended. An easy way to save energy is to shut down some of the mixers during certain periods whilst monitoring the effect on the efficiency of the denitrification. The inlet pumps are run based on the influent flow rate. This is necessary because the denitrification basins are built higher up than the surrounding processes. An approximate ranking of the individual energy consumers in the denitrification process can be seen below in Table 7.4.

Object	**% of total electrical energy usage in the denitrification process**
Mixers	66
Inlet pumps	33

Table 7.4 Ranking of individual consumers in the denitrification process at Sjölunda WWTP

7.1.5 Anaerobic digestion

There are more energy consumers in the anaerobic digestion tanks than shown in Table 7.5, but they are both small and have short run-time. All three mentioned are used to create motion in the sludge to ensure that the conditions are suitable for digestion. The circulation pumps are also used when the reactors are emptied of digested sludge and filled with new sludge. This process involves pumping the influent sludge through heat exchangers to raise the temperature, both with the help of the outgoing sludge and with the help of the plant's internal heat system. No electricity is used directly to heat the sludge to the desired 33°C. This of course lowers the electrical energy consumption, but it increases the amount of heat used instead.

Object	**% of total electrical energy usage in the anaerobic digestion process**
Circulation pumps	56
Gas compressors	32
Mechanical mixers	12

Table 7.5 Ranking of individual consumers in the anaerobic digestion process at Sjölunda WWTP

7.1.6 Flow equalization

The equalization pumps are used to equalize the influent flow rate and reduce the flow peaks into the plant. This reduces the stress on the process control and results in a more even load. It is not clear whether this is necessary or not, and the same thing can be accomplished by the pumping stations of the pipe network instead. This will, however, be looked into at a later point in time, when the currently ongoing construction of the overflow storage tanks are finished.

7.2 Klagshamn WWTP

As for Sjölunda WWTP, the main processes that together consume close to 80% of the total electrical energy are further investigated. The top five electrical energy consuming processes can be seen again in Table 7.6.

Process	**% of total electrical energy usage**
Activated sludge	33
Denitrification	15
Inlet pumps	14
Anaerobic digestion	11
Sludge dewatering	6.8

Table 7.6 Top five individual energy consumers at Klagshamn WWTP

7.2.1 Activated sludge

As seen in Table 7.7, the blowers use about 2/3 of the energy used in the activated sludge process. The blowers are well controlled, with oxygen sensors in four of the nine sections of each process. There is always the possibility of changing motors and aeration equipment for more efficient ones, but this is expensive and time consuming. It also requires an extensive study to investigate how large the savings could be. Looking into the the set values for the oxygen levels are also a good idea. The mixers and scrapers are most likely the easiest candidates to reduce the energy consumption of, if it is possible to run them intermittently without affecting the efficiency of the treatment process. It might also be possible to shut down some of the mixers if the remaining ones can maintain an adequate mixing in the process.

Object	**% of total electrical energy usage in the activated sludge process**
Blowers	64
Sludge pumps	21
Mixers	11
Scrapers	1.4

Table 7.7 Ranking of individual consumers in the activated sludge process at Klagshamn WWTP

7.2.2 Denitrification

The three inlet pumps are controlled based on the wastewater level in the inlet basin, and strive to keep the level constant. The mixers are used to keep the carrier material in the basins suspended, and the blower is used to clean the grid that keeps the carriers inside the basins. It might, for example, be possible to use a different mixer and perhaps tune the power of the motors driving them, thus lowering the energy consumption in the process. Here, as well as in the activated sludge process, tests should be performed to investigate if the process can be run with some of the mixers turned off and still maintain its denitrification efficiency. An approximate ranking of the individual energy consumers in the denitrification process can be seen below in Table 7.8.

Object	**% of total electrical energy usage in the denitrification process**
Inlet pumps	54
Mixers	45
Blowers	1.2

Table 7.8 Ranking of individual consumers in the denitrification process at Klagshamn WWTP

7.2.3 Inlet pumps

The three inlet pumps are controlled depending on the influent flow rate to the plant. Two of them are speed controlled and the last one is on-off controlled. These are used to lift the wastewater to the plant, and they are also used, together with the sewers to smooth out the influent flow rate and reduce peaks. The inlet pumps are screw type pumps, which is a suitable choice for this purpose. They are insensitive to materials in the influent and are easily regulated. The saving potential is small in this stage. More efficient motors are one way of reducing the energy consumption but this of course introduces investment costs.

7.2.4 Anaerobic digestion

The circulation pumps are used both for circulation of the sludge inside the reactor and for transport through the three heat exchangers that are used for heating the sludge. The compressors are also used for mixing the sludge by injecting the produced gas into the bottom of the reactors and up through the sludge. Saving energy in this stage involves reducing the amount of sludge pumped through the heat exchangers. It might be possible to reduce the amount of preheating, and thus lowering the energy used by the pumps, without affecting the gas production too much. On the other hand, a higher gas production means that less electrical energy has to be bought from an external supplier, thus lowering the costs. Examinations will have to be made to determine if this is possible. An approximate ranking of the individual energy consumers in the anaerobic digestion process can be seen below in Table 7.9.

Object	**% of total electrical energy usage in the anaerobic digestion process**
Circulation pumps	62
Compressors	38

Table 7.9 Ranking of individual consumers in the anaerobic digestion process at Klagshamn WWTP

7.2.5 Sludge dewatering

The most energy consuming objects in the sludge dewatering stage are the two centrifuges. They reduce the water content of the sludge from 97% to about 80%. Gravitational thickeners are used before and after the anaerobic digestion for removing some of the water from the sludge. The conveyers and pumps transport the sludge between the digesters, the gravitational thickeners and the centrifuges. Again, there is not any major obvious saving potential. If the centrifuges are not run all the time, their operation should be timed so that the peak energy consumption of the plant is kept as low as possible. For the transporters, more efficient motors represent one possible option for lowering energy consumption. An approximate ranking of the individual energy consumers in the dewatering process can be seen below in Table 7.10.

Object	**% of total electrical energy usage in the sludge dewatering process**
Centrifuges	61
Conveyors	24
Pumps	13
Gravitational thickeners	0.8

Table 7.10 Ranking of individual consumers in the sludge dewatering process at Klagshamn WWTP

7.3 Recommendations and conclusions

In general, we would recommend that the greatest effort is spent on studying the largest processes. It is likely that it is there the largest savings can be made. We believe that it is a good idea to evaluate energy consumption from a process perspective rather than for each individual consumer. When studying a process, the main focus should be on the largest consumer group.

Another general recommendation is to evaluate the run-times of all groups of small energy consumers to see if some of them can be run intermittently or even closed down without affecting the overall results of the treatments.

All equipment should be kept clean and well serviced to maintain their factory specifications. Worn parts should be exchanged, and a maintenance schedule should be used to make sure that no parts are overlooked.

7.3.1 Sjölunda WWTP

Based on the discussions in the previous sections we would recommend the following with regard to Sjölunda WWTP.

- Start looking at the largest processes. The activated sludge process, the flotation process and the trickling filters separate themselves from the others by representing more than 17 % each of the total energy consumption. As seen in the special case study of the activated sludge process there is much to be further evaluated. For example, the control of the aeration system and the possibility of combining the return activated sludge pumping with the inlet pumping in G4. The trickling filters do not present such an opportunity for savings though, consisting of only five pumps.

- Secondly we would recommend that the anaerobic digestion and the denitrification are evaluated. The flow equalization pumps are in some way a group of its own since the need for it should be discussed before its energy consumption is evaluated.

- Install power meters so that the consumption of the individual processes can be monitored without more advanced calculations than subtraction. We also think that the possibility to monitor the run-times of all consumers should be evaluated since having the run-times available would greatly simplify all work along the lines of energy conservation.

7.3.2 Klagshamn WWTP

Based on the discussions in the previous sections we would recommend the following with regard to Klagshamn WWTP.

- Start looking at the largest processes. Activated sludge, denitrification and inlet pumping are the largest processes. The inlet pumping would probably be the least interesting from an energy saving perspective.

- After the largest processes are analysed move on to the anaerobic digestion and sludge dewatering processes.

- Install power meters so that the consumption of the individual processes can be monitored without more advanced calculations than subtraction.

The recommendations for the two WWTPs are similar. It is likely that much can be obtained by introducing energy conservation thinking to the organisation. First and foremost it is important to make way for further work along these lines by building a working structure for analysis. At Klagshamn the run-time measurements make a good start but at Sjölunda something will need to be done. Energy conservation should be a natural part of wastewater treatment operation, but this requires a platform to work from.

8 Performance indicators

To make wastewater treatment economic and efficient there has to be ways of measuring the performance. One way to keep track of the performance is the use of so called performance indicators, which are quantitative measurements designed for monitoring a special aspect of the process. They can be used in a range of different ways and in various areas of the plant management. Performance indicators can be used to evaluate the process, the economic management, the service vis-à-vis the customer, the productivity of the human resources etc. They can, of course, also be used to monitor the energy efficiency of the whole process and the different individual process stages. The focus of this chapter is on energy related performance indicators in wastewater treatment (Alegre et al., 2000).

8.1 The aim of performance indicators

When constructing performance indicators it is of vital importance that the aim of the indicator is clearly decided upon. As mentioned above, there are many different usages for performance indicators. They can be used for evaluating the effect of changes in the control of a process or the installation of new equipment, for monitoring the efficiency of the process during different conditions, for comparing two parallel lines of the same process, for comparing different WWTPs, for yearly statistics etc. The main rule is that the definition should be decided by the purpose, of what the indicator is supposed to show.

8.1.1 Evaluation of changes

Changes related to equipment or the control of a process must be evaluated. Most important is to evaluate the performance with respect to wastewater quality but with energy conservation in mind. It is also important to evaluate the effect on the energy efficiency. When defining performance indicators for this purpose a lot of different aspects have to be taken into consideration. The measurements have to be normalized so that fluctuations in temperature, wastewater quality and flow rate do not affect the evaluation.

8.1.2 Efficiency during different conditions

A wastewater process is subject to many different uncontrollable factors, such as changes in weather and temperature, flow rate variations on both daily and yearly basis, changes in levels of contaminants and overall changes of the wastewater composition. There are several reasons for studying the performance of a process during different conditions. From an energy point of view it can be helpful in the design of the control algorithms and the selection of equipment. When constructing an indicator for studying performance at, for instance, different temperatures all other changes have to be normalized to avoid erroneous and biased results.

8.1.3 Comparisons

When studying energy efficiency it is interesting to compare processes. It can be about comparing activated sludge processes at different plants or different lines of the denitrification process at a single plant or about comparing anaerobic digestion with lime stabilization as methods for sludge stabilization. There are different things to consider when designing indicators for internal and external comparisons.

8.1.3.1 Internal comparisons

When designing for internal comparison normalization for factors such as the wastewater composition and temperature is sometimes unnecessary. When different lines of the same process shall be compared this is often the designers purpose, but it is not always the case. It is safest to check the flow rates and concentrations that are of interest to make sure that the different lines have the same operating conditions. If the lines in question differ in design or if there is a difference in influent flow rate this has to be taken into account.

8.1.3.2 External comparisons

When comparing different WWTPs it is again important to normalize for factors such as wastewater quality, flow rate and weather conditions. Differences in design and dimensioning must also be considered. Again it is the purpose of the indicator that has to decide. For example, if the purpose is to study the difference between different kinds of aeration systems in activated sludge applications this design difference should not, of course, be eliminated but maybe there are some elevations or different kind of pumps for the return activated sludge that should not be allowed to affect the result.

8.1.4 Statistics

Efficiency indicators used for statistic purposes often aim at showing the fluctuations in weather, flow rate, etc. Then, of course, these factors should not be eliminated.

8.2 Units

As well as choosing what factors should be eliminated, the unit of the indicator has to be decided upon. Again it depends on what the indicator is supposed to be used for. As energy is the target in this work, the focus here will be energy related units. When talking about energy efficiency it is natural that kWh is a part of the unit, but kWh per what?

It is close at hand to think kWh/m^3 or kWh/p.e. These are useful units in some cases. Other examples of units are kWh/kg nitrogen reduced or kWh/kg phosphor reduced. Choosing what unit to use for a performance indicator introduces new design obstacles. The characteristics of the chosen unit have to be taken into consideration as well. for example if the unit in question is kWh/kg nitrogen reduced and the process studied is a denitrification process the fact that the nitrogen removal is a non linear process, which is more efficient when the concentration is higher, has to be accounted for.

8.3 Time scale

When designing and planning the use of performance indicators for different aspects it is important to reflect on the time scale. It is possible that a performance indicator will give quite different results if the time scale is hours instead of months. What time scale to choose depends, of course, on the aim of the performance indicator. Looking at a performance indicator over a year will show seasonal fluctuations but hide daily variations and studying the same indicator over a day or two would do the opposite.

8.4 Design of performance indicators

This section deals, concretely, with the process of designing performance indicators. One procedure for such design will be studied and used in a few examples. Three different cases from Sjölunda have been chosen to illustrate the process of designing performance indicators.

8.4.1 kWh/p.e.

A somewhat classic performance indicator while studying energy in wastewater treatment would be kWh/p.e. The main purpose is to look at the process over a long period of time and therefore there is not much normalization to consider. On the other hand, it is important to be precise about which definition of p.e. is used. This is once again one of the areas where some standardisation would simplify.

The definition of p.e. varies widely both nationally and internationally. In the Environmental Reports from Sjölunda and Klagshamn WWTPs, three different definitions are mentioned. These are calculated with respect to BOD_7, nitrogen and influent waste water flow. When calculating the number of p.e.s with respect to BOD_7 the total, daily, amount of incoming BOD_7 is divided by 70, since 70 grams is a standard value for the amount of BOD_7 from one person. When calculating based on the flow rate, the daily influent flow rate of sewage, in litres, is divided by 181, since 181 is the estimate, used by Sjölunda and Klagshamn WWTPs, of how much sewage one person produces during one day. When calculating for nitrogen the total daily amount of nitrogen is divided by 11 g which is the estimated nitrogen production from one person during one day.

The performance indicator itself is in this case as simple as dividing the yearly energy consumption in kWh with the calculated number of p.e.s. Figures 8.1-8.3 show the performance indicators plotted over the last twelve years for Sjölunda. All values used for the construction of the diagrams were taken from the Environmental Reports. When calculating p.e. based on sewage influent the Environmental Reports contained only a calculated value of the sewage from Malmö. Sjölunda WWTP treats wastewater from adjacent municipalities as well and for those no sewage flows were stated. To overcome this problem the ratio between sewage and wastewater flow rate in Malmö was used to estimate the needed value.

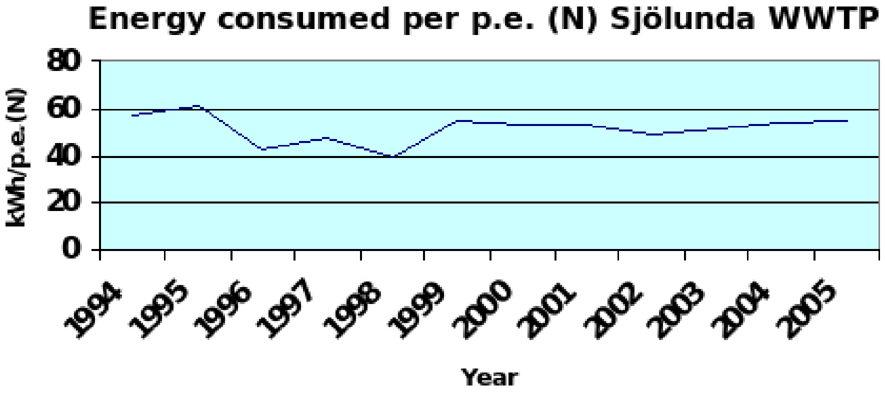

Figure 8.3 Energy consumed per p.e. (N) at Sjölunda WWTP

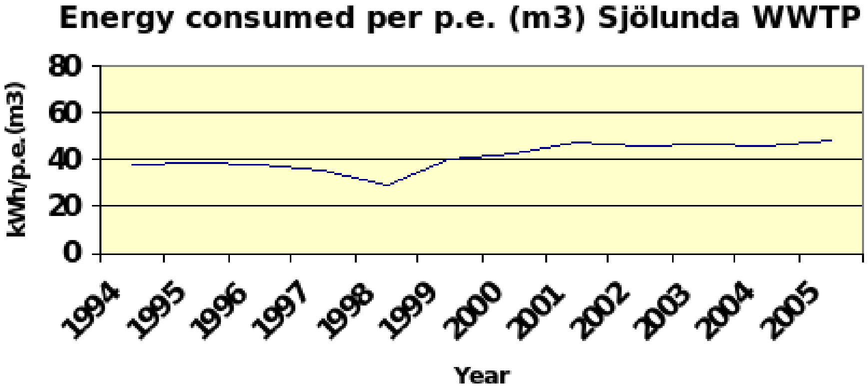

Figure 8.1 Energy consumed per p.e. (m^3) at Sjölunda WWTP

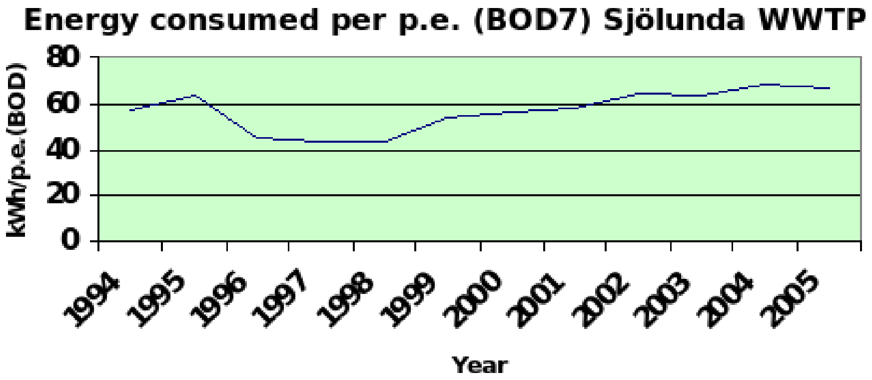

Figure 8.2 Energy consumed per p.e. (BOD_7) at Sjölunda WWTP

Figures 8.4-8.6 present the corresponding diagrams for Klagshamn WWTP, showing the performance indicator with the different definitions for p.e. for the last ten years. All values are taken from the Environmental Reports.

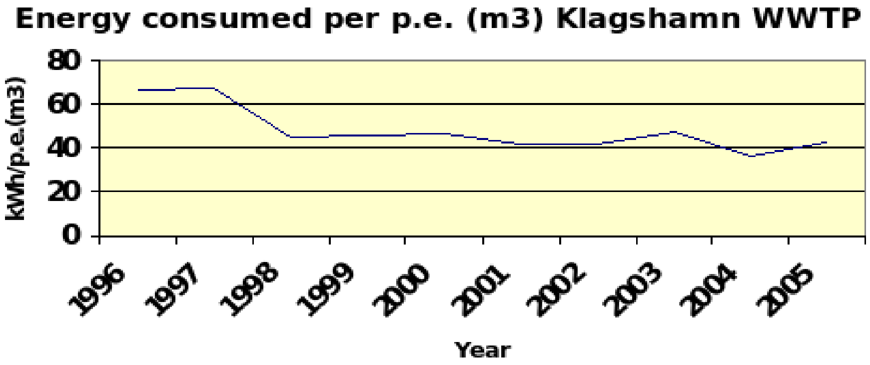

Figure 8.4 Energy consumed per p.e. (m^3) at Klagshamn WWTP

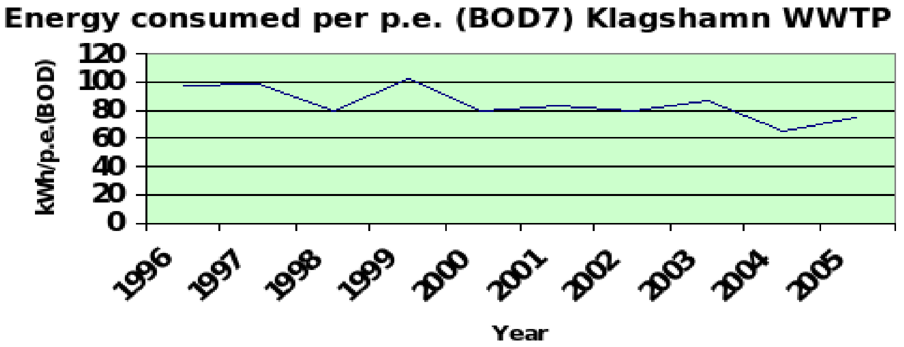

Figure 8.5 Energy consumed per p.e. (BOD_7) at Klagshamn WWTP

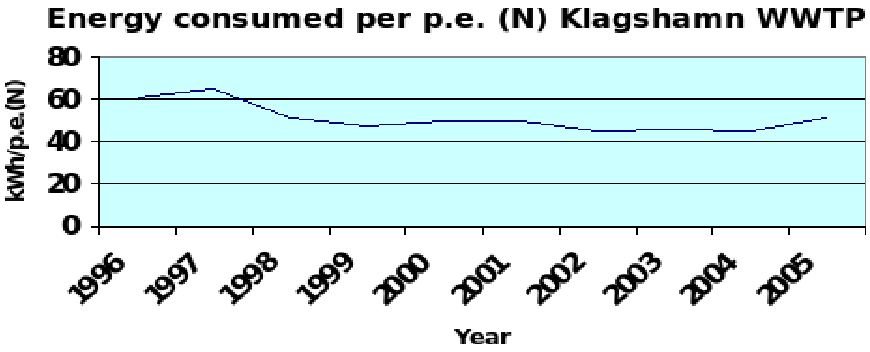

Figure 8.6 Energy consumed per p.e. (N) at Klagshamn WWTP

The differences in the diagrams show how important it is to know in what way the indicator is constructed. They also indicate that it is important to know what has happened during the years studied. Without knowledge about new installations and changed regulations they are more confusing than clarifying, but with the right background they can provide a significant amount of information.

About the diagrams it can be noted that the trend is very similar in the three diagrams for Sjölunda and the three diagrams for Klagshamn, respectively. Another thing to reflect upon is that if the definitions of p.e. were perfect, the curves should look the same independently of which p.e. definition was used.

8.4.2 Automatic control of air flow rate

In 1990, automatic control of the air flow to the activated sludge process was introduced at Klagshamn WWTP. This is typically a change when the energy consumption before and after should be evaluated. This can be done simply by studying the energy consumption over time. Before the automatic control system was installed the power varied around one hundred kW and after the installation around sixty kW, see Figure 8.7 (Andersson – Hansson, 1990).

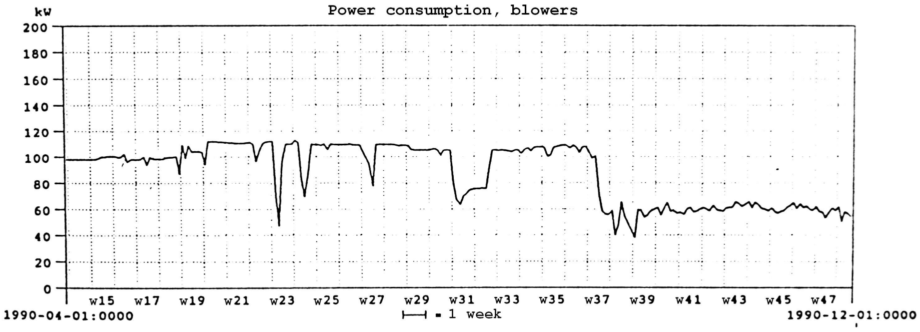

Figure 8.7 Power consumption by the blowers at Klagshamn WWTP

The diagram above shows a considerable reduction in energy consumption and since energy over time is what is paid for, it actually means a decrease in cost.

The control algorithm was set to keep the oxygen level at 2 mg O_2/l since that should be enough for the process. If kW/mg oxygen was studied instead other results would be indicated, since the oxygen level was appreciably higher before the installation, see Figure 8.8 below. Since 2 mg O_2/l should be more than enough this should not matter when studying energy consumption, assuming that the results of the treatment process do not deteriorate.

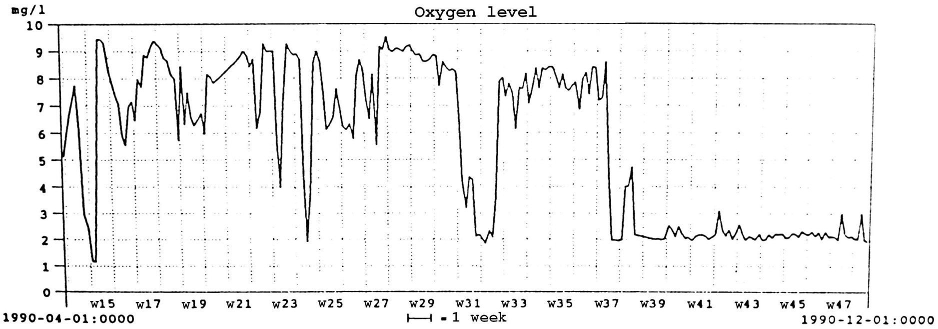

Figure 8.8 Oxygen level in the activated sludge process at Klagshamn WWTP

Another, maybe more quality oriented, way to study the effects of the new installation on the energy consumption would be to analyse at energy consumption as a function of BOD_7 reduced. In this case no data for doing so is obtainable.

8.4.3 Mixer energy usage

Figure 8.9 Denitrification with suspended carriers

Sjölunda and Klagshamn WWTPs use the same denitrification method with suspended carriers, as shown in Figure 8.9. This method of denitrification use mixers to keep the carriers suspended in the wastewater. It can be interesting to study the differences in energy consumed by the mixers. Since the amount of wastewater that flows through the process differ between the two WWTPs it can be interesting to look at mixer energy/m^3. Figure 8.10 below shows mixer energy per m^3 influent wastewater from Sjölunda and Klagshamn WWTPs during the first six months 2007.

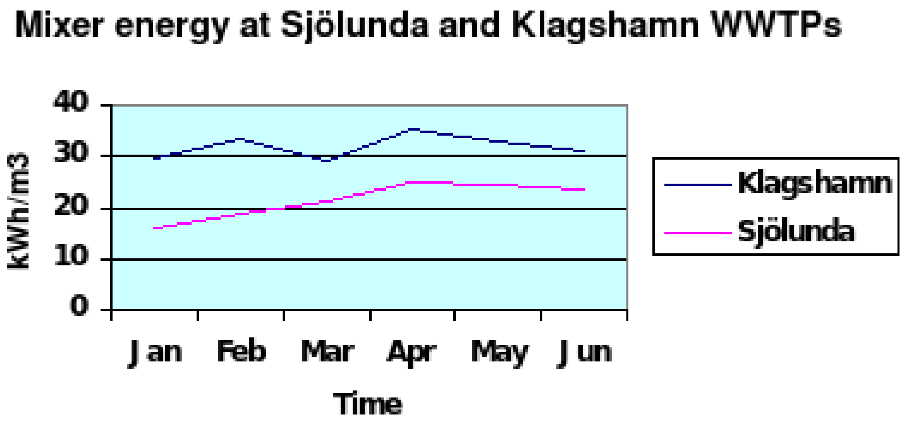

Figure 8.10 Energy used by the mixers in the denitrification processes

As is clearly shown in the diagram, the energy used for mixing the wastewater is significantly lower at Sjölunda than at Klagshamn. Before jumping to any conclusions this result must be interpreted; what reasons can there be for such a result? Could it just be that the process at Sjölunda is much larger? Could it be that the degree of filling is higher at Sjölunda (50 %) than at Klagshamn (33 %)? Could it be the wastewater quality or is it just how the processes are controlled? Before knowing the answers to these questions and probably others as well, no valid conclusions can be drawn. If the answer is yes to one of the questions presented it could be interesting to normalize for this factor and analyse the results again.

8.4.4 Further examples

Another way to study the efficiency of for example a denitrification process or an entire plant, would be kWh per kg nitrogen reduced. Since the efficiency of the nitrogen reduction is dependent on the nitrate concentration such a performance indicator would possibly have to be normalized for the flow rate. This would give a unit like kWh per kg nitrogen reduced per m^3.

8.5 Documentation

It is very important to document the performance indicators to prevent them from being used the wrong way, resulting in misleading interpretations. As well as preventing errors the documentation can be an asset when constructing new indicators or when evaluating the existing set.

8.6 Standards

As in many other cases there is much to gain from introducing standards for the use and construction of performance indicators. Standards, on both national and international basis, would increase the possibilities to learn from other WWTPs and for comparing different process types during different conditions etc.

9 Conclusion

This chapter includes conclusions based on the results of this master thesis, some reflections on the results and a section about future work.

9.1 Results

This master thesis has resulted in inventories of the electrical energy usage at Sjölunda and Klagshamn WWTPs, energy conservations plans for the two WWTPs and a discussion about the usage of performance indicators for studying energy conservation in wastewater operation. The evaluation of these two WWTPs together with the indications from different reports on a saving potential of 10-30 % in Swedish WWT operation shows that there is a potential of decreasing the energy consumption.

The inventories show that the different processes' energy usage is fairly similar at the two WWTPs. Of course there are differences, but most of them can be related to the differences in the treatment processes. The recommendations in the energy conservation plans are similar as well. This should not be surprising for two plants under one management and with similar quality of the influent wastewater. Some of the differences can be explained by the different sizes of the plants. A large plant is always likely to have a slightly smaller relative energy usage and so is the case with these plants as well.

9.2 Reflections

After concluding the work with this thesis one result stands out from the others; the need for a well defined structure for working with energy conservation. This is connected to all three main parts of this project. The ability of constructing a valid inventory with specified energy usage for the different processes fall back on the need for a way to measure the usage of each process separately. When evaluating a process, trying to find ways to make it more energy efficient, it would be a great help to know the run-times of the different objects. Last but not least, there has got to be a well defined way to measure the results, which could be obtained by using the right performance indicators.

After working with this for some months we feel strongly that it is important to simplify the procedures involved in working with energy at both plants. As it is today it is too time consuming to gather the necessary data. There is a general feeling that the structure is not suitable for this kind of evaluation. We believe that this a key to future successful energy conservation at Sjölunda and Klagshamn.

9.3 Future work

The effort to make use of the full saving potential at Sjölunda and Klagshamn may seem long, but we believe that providing a foundation of data to work with and introducing energy thinking in the organization is a good start. Then it would be easier to go on with further analyses. Another possibility is to start from the other end by designing a set of performance indicators for evaluating the results of different actions. Starting in this end would have the advantage that all changes could be evaluated directly.

None of these approaches would probably lead to any immediate savings, but would provide a strong foundation for further work. For faster results there is of course the possibility of starting evaluating the largest processes, but without more data available this would be likely to consume unnecessary amounts of time.

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Appendix A – Consumers at Sjölunda WWTP

Process	Object	Rated power (kW)	Total usage (kWh
Equalizing			
	Pump	75	
	Pump	75	
	Pump	75	
			931395
Screens			
	Pump	1.5	
	Screen	5.5	
	Screen	5.5	
	Screen	5.5	
	Screen	5.5	
	Transporter	4	
	Transporter	4	
	Transporter	7.5	
	Transporter	7.5	
	Motor	0.37	
	Motor	0.37	
	Motor	2.2	
	Motor	2.2	
	Motor	1.5	
	Motor	1.5	
	Motor	1.5	
	Motor	1.5	
	Motor	1.5	
	Motor	1.5	
	Motor	1.5	
	Motor	0.37	
	Motor	0.37	
	Motor	0.37	
	Motor	0.37	
	Transporter	5.5	
	Transporter	5.5	
	Transporter	4	
	Transporter	4	
	Transporter	5.5	
	Transporter	5.5	
	Transporter	4	
	Transporter	4	
			38473
Grit removal and primary sedimentation			
	Scraper	0.75	
	Pump	7.5	
	Pump	7.5	
	Pump	5.85	
	Blower	55	
	Blower	55	

	Blower	45	
	Pump	5.9	
	Scraper	0.75	
	Pump	4.7	
	Pump	5.9	
	Pump	5.85	
	Pump	5.9	
	Blower	55	
	Blower	55	
	Blower	45	
	Transporter	1.5	
	Transporter	1.5	
	Transporter	1.5	
	Transporter	1.5	
	Transporter	1.5	
	Transporter	1.1	
	Transporter	1.1	
	Pump	7.5	
	Pump	7.5	
	Grit washer	0.55	
	Transporter	1.1	
	Grit washer	0.55	
	Transporter	1.1	
	Pump	13	
	Pump	13	
	Pump	7.5	
	Pump	7.5	
	Scraper	2	
	Scraper	2	
	Scraper	2	
	Scraper	2	
	Pump	13	
	Pump	7.5	
	Pump	13	
	Pump	7.5	
	Scraper	2	
	Scraper	2	
	Scraper	2	
	Scraper	2	
	Pump	2.2	
	Pump	2.2	
	Mixer	4	
	Mixer	3	
			634803
Activated sludge			
G1	Scraper	1.5	
	Scraper	1.5	
	Scraper	1.5	

	Scraper	1.5	
	Blower	75	
	Blower	65	
	Pump	3.7	
	Pump	2.7	
	Pump	2.2	
	Pump	2.2	
	Pump	2.2	
	Pump	2.2	
	Pump	2.2	
	Pump	2.2	
	Pump	2.2	
	Pump	2.2	
	Pump	2.2	
	Pump	2.2	
	Pump	2.2	
	Pump	2.2	
	Mixer	2.21	
	Mixer	2.21	
	Mixer	2.21	
G2	Scraper	3.3	
	Scraper	3.3	
	Scraper	3.3	
	Scraper	3.3	
	Scraper	3.3	
	Scraper	3.3	
	Scraper	3.3	
	Scraper	3.3	
	Blower	75	
	Blower	90	
	Pump	5.5	
	Pump	5.5	
	Pump	2.2	
	Pump	2.2	
	Pump	2.2	
	Pump	2.2	
	Pump	2.2	
	Pump	2.2	
	Pump	2.2	
	Pump	2.2	
	Pump	2.2	
	Pump	2.2	
	Pump	2.2	
	Pump	2.2	
	Blower	90	
	Mixer	1.5	
	Mixer	1.5	
	Mixer	1.5	
	Mixer	1.5	
	Mixer	1.5	

	Mixer	1.5	
	Mixer	1.5	
	Mixer	1.5	
G3	Scraper	3.3	
	Scraper	3.3	
	Scraper	3.3	
	Scraper	3.3	
	Scraper	3.3	
	Scraper	3.3	
	Scraper	3.3	
	Scraper	0.25	
	Pump	5.5	
	Pump	5.5	
	Pump	2	
	Pump	2	
	Pump	2	
	Pump	2	
	Pump	2	
	Pump	2	
	Pump	2	
	Pump	2	
	Pump	2	
	Pump	2	
	Pump	2	
	Pump	2	
	Blower	90	
	Blower	90	
	Blower	90	
	Mixer	*1.5*	
	Mixer	*1.5*	
G4	Pump	75	
	Pump	75	
	Pump	75	
	Pump	55	
	Mixer	1.5	
	Mixer	1.5	
	Mixer	1.5	
	Mixer	1.5	
	Mixer	1.5	
	Mixer	1.5	
	Mixer	1.5	
	Mixer	1.5	
	Mixer	1.5	
	Pump	75	
	Pump	75	
	Pump	75	
	Pump	55	
	Blower	200	
	Blower	250	
	Blower	200	

	Blower	18.5	
	Pump	18.5	
	Pump	18.5	
	Scraper	1.5	
	Scraper	1.5	
	Scraper	1.5	
	Scraper	1.5	
	Scraper	1.5	
	Scraper	1.5	
	Mixer	1.2	
	Mixer	1.2	
	Scraper	1.5	
	Scraper	1.5	
	Scraper	1.5	
	Scraper	1.5	
	Scraper	1.5	
	Scraper	1.5	
	Scraper	1.5	
	Scraper	1.5	
			5342099
Trickling filters			
	Pump	90	
	Pump	90	
	Pump	132	
	Pump	132	
	Pump	132	
			3076351
Denitrification			
	Pump	0.18	
	Pump	0.18	
	Pump	0.18	
	Pump	0.18	
	Pump	0.18	
	Pump	0.18	
	Pump	2.5	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Pump	1.2	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Mixer	4	

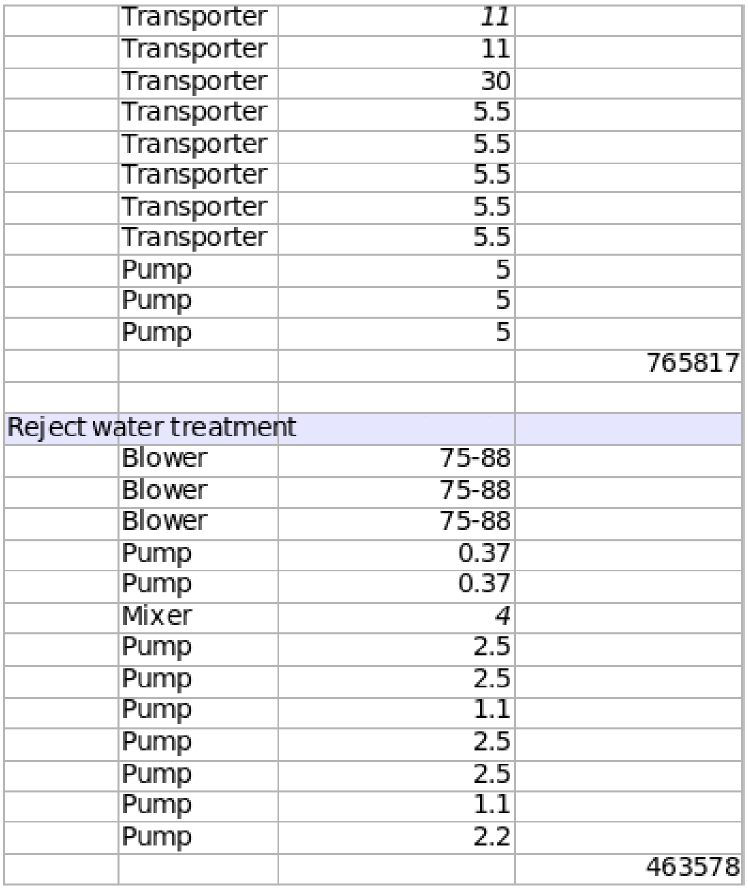
	Pump	1.2	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Pump	1.2	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Pump	1.2	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Pump	1.2	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Mixer	4	
	Mixer	4	
			1145878
Flotation			
	Pump	45	
	Pump	45	
	Transporter	0.25	
	Transporter	0.25	
	Transporter	0.25	
	Transporter	0.25	
	Pump	0.34	
	Pump	0.37	
	Pump	212	
	Pump	110	
	Pump	110	
	Pump	110	
	Pump	110	
	Pump	110	
	Scraper	0.75	
	Scraper	0.75	
	Scraper	0.75	
	Scraper	0.75	
	Scraper	0.75	

	Scraper	0.75	
	Scraper	0.75	
	Scraper	0.75	
	Transporter	4	
	Transporter	4	
	Mixer	0.55	
	Mixer	0.55	
	Mixer	0.37	
	Mixer	0.37	
	Mixer	0.55	
	Mixer	0.55	
	Mixer	0.37	
	Mixer	0.37	
	Mixer	0.55	
	Mixer	0.55	
	Mixer	0.37	
	Mixer	0.37	
	Mixer	0.55	
	Mixer	0.55	
	Mixer	0.37	
	Mixer	0.37	
	Scraper	0.75	
	Scraper	0.75	
	Scraper	0.75	
	Scraper	0.75	
	Scraper	0.75	
	Scraper	0.75	
	Scraper	0.75	
	Scraper	0.75	
	Transporter	4	
	Transporter	4	
	Mixer	0.55	
	Mixer	0.55	
	Mixer	0.37	
	Mixer	0.37	
	Mixer	0.55	
	Mixer	0.55	
	Mixer	0.37	
	Mixer	0.37	
	Mixer	0.55	
	Mixer	0.55	
	Mixer	0.37	
	Mixer	0.37	
	Mixer	0.55	
	Mixer	0.55	
	Mixer	0.37	
	Mixer	0.37	
	Scraper	0.75	
	Scraper	0.75	
	Scraper	0.75	

	Scraper	0.75	
	Scraper	0.75	
	Scraper	0.75	
	Scraper	0.75	
	Scraper	0.75	
	Transporter	4	
	Transporter	4	
	Mixer	0.55	
	Mixer	0.55	
	Mixer	0.37	
	Mixer	0.37	
	Mixer	0.55	
	Mixer	0.55	
	Mixer	0.37	
	Mixer	0.37	
	Mixer	0.55	
	Mixer	0.55	
	Mixer	0.37	
	Mixer	0.37	
	Mixer	0.55	
	Mixer	0.55	
	Mixer	0.37	
	Mixer	0.37	
	Scraper	0.75	
	Scraper	0.75	
	Scraper	0.75	
	Scraper	0.75	
	Scraper	0.75	
	Scraper	0.75	
	Scraper	0.75	
	Scraper	0.75	
	Transporter	4	
	Transporter	4	
	Mixer	0.55	
	Mixer	0.55	
	Mixer	0.37	
	Mixer	0.37	
	Mixer	0.55	
	Mixer	0.55	
	Mixer	0.37	
	Mixer	0.37	
	Mixer	0.55	
	Mixer	0.55	
	Mixer	0.37	
	Mixer	0.37	
	Mixer	0.55	
	Mixer	0.55	
	Mixer	0.37	
	Mixer	0.37	
	Pump	11	

	Pump	11	
	Pump	11	
	Pump	11	
	Mixer	*0.37*	
	Mixer	*0.55*	
	Mixer	*0.37*	
	Mixer	*0.55*	
	Pump	4	
	Pump	4	
	Pump	4	
	Pump	4	
			3116287
Sludge thickening			
	Pump	8.5-13	
	Pump	15	
	Pump	15	
	Pump	7.5	
	Pump	7.5	
	Pump	7.5	
	Scraper	1.8	
	Scraper	1.8	
	Scraper	1.8	
	Pump	7.5	
	Motor	1.5	
	Transporter	0.75	
	Transporter	0.75	
	Transporter	1.1	
	Press	*1*	
	Mixer	2.2	
	Mixer	*2.2*	
	Pump	11	
	Pump	11	
	Pump	11	
	Pump	5.5	
	Pump	5.5	
	Pump	15	
			288547
Anaerobic digestion			
	Pump	7.4	
	Pump	7.4	
	Pump	7.5	
	Pump	7.5	
	Pump	7.5	
	Compressor	34	
	Mixer	3.6	
	Mixer	*3.6*	
	Mixer	*1.5*	
	Mixer	*1.5*	

	Compressor	34	
	Mixer	1.5	
	Mixer	1.5	
	Pump	7.5	
	Pump	7.5	
	Pump	7.5	
	Pump	7.5	
	Pump	7.5/8.6	
	Pump	11	
	Pump	4	
	Pump	7.5	
	Mixer	1.35	
	Mixer	5.5	
	Mixer	1.35	
	Mixer	5.5	
	Pump	15	
	Pump	15	
	Pump	15	
	Pump	11	
	Pump	5.5	
	Pump	3	
	Pump	1.1	
			1048492
Sludge dewatering			
	Centrifuge	*18.5*	
	Centrifuge	18.5	
	Centrifuge	18.5	
	Pump	5.5	
	Pump	7.5	
	Pump	5.5	
	Pump	1.5	
	Pump	2.2	
	Pump	1.5	
	Pump	1.1	
	Pump	4	
	Pump	0.18	
	Pump	0.18	
	Mixer	0.55	
	Mixer	0.55	
	Pump	1.5	
	Pump	1.5	
	Pump	4	
	Pump	4	
	Pump	0.15	
	Pump	0.15	
	Mixer	*1.5*	
	Mixer	*1.5*	
	Transporter	*1.5*	
	Transporter	11	



	Transporter	*11*	
	Transporter	11	
	Transporter	30	
	Transporter	5.5	
	Transporter	5.5	
	Transporter	5.5	
	Transporter	5.5	
	Transporter	5.5	
	Pump	5	
	Pump	5	
	Pump	5	
			765817
Reject water treatment			
	Blower	75-88	
	Blower	75-88	
	Blower	75-88	
	Pump	0.37	
	Pump	0.37	
	Mixer	*4*	
	Pump	2.5	
	Pump	2.5	
	Pump	1.1	
	Pump	2.5	
	Pump	2.5	
	Pump	1.1	
	Pump	2.2	
			463578

Appendix B – Consumers at Klagshamn WWTP

Process	Object	Rated power (kW)	Runtime (h)[1]	Energy usage (kWh)[2]	Total usage (kWh)
Inlet					
	Pump	112.2	4619	414601.44	
	Pump	160	144	18432	
	Pump	113	4114	371905.6	
					804939.04
Screens					
	Hydr. unit	3	26	62.4	
	Press	3	183	439.2	
	Screen	3	581	1394.4	
	Screen	0.06/1.3	8/38	39.9	
	Screen	0.06/1.3	9/41	43.07	
	Screw	3	183	439.2	
	Transporter	3	31	74.4	
	Transporter	7.5	1094	6564	
	Transporter	1.1	282	248.16	
					9304.74
Grit removal and primary sedimentation					
	Blowers[3]			70158	
	Mixer	0.18	1025	147.6	
	Mixer	0.18	1025	147.6	
	Mixer	0.18	1023	147.31	
	Mixer	0.18	1059	152.5	
	Pump	0.09	8722	627.98	
	Pump	1.3	17	17.68	
	Pump	8.5	146	992.8	
	Pump	15	170	2040	
	Pump	5.5	777	3418.8	
	Pump	0.09	8751	630.07	
	Pump	5.5	798	3511.2	
	Pump	7.5	2143	12858	
	Pump	7.5	2142	12852	
	Pump	11	547	4813.6	
	Pump	15	147	1764	
	Scraper	3.55	1223	3473.32	
	Scraper	3.55	1059	3007.56	
	Scraper	1.3	2391	2486.64	
	Scraper	1.3	2351	2445.04	
	Scraper	1.3	2352	2446.08	
	Scraper	1.3	2352	2446.08	
					130583.86

Activated sludge					
	Blowers[3]			474418.8	
	Drum	1.1	186	163.68	
	Drum	1.1	187	164.56	
	Mixer	1.5	8746	10495.2	
	Mixer	1.5	4191	5029.2	
	Mixer	1.5	4191	5029.2	
	Mixer	1.5	4191	5029.2	
	Mixer	1.5	4191	5029.2	
	Mixer	1.5	8746	10495.2	
	Mixer	1.5	8746	10495.2	
	Mixer	1.5	8746	10495.2	
	Mixer	1.5	8746	10495.2	
	Mixer	1.5	8746	10495.2	
	Pump	11	8745	76956	
	Pump	11	8745	76956	
	Pump	5.5	1169	5143.6	
	Pump	5.5	547	2406.8	
	Pump	11	298	2622.4	
	Pump	11	254	2235.2	
	Pump	11	265	2332	
	Pump	11	239	2103.2	
	Scraper	0.18	8745	1259.28	
	Scraper	0.18	8745	1259.28	
	Scraper	0.18	8745	1259.28	
	Scraper	0.18	8745	1259.28	
	Scraper	0.18	8745	1259.28	
	Scraper	0.18	8745	1259.28	
	Scraper	0.18	8745	1259.28	
	Scraper	0.18	8745	1259.28	
					738664.48
Denitrification					
	Blower	36	62	1785.6	
	Blower	45	63	2268	
	Mixer	5.6	8747	39186.56	
	Mixer	5.6	8566	38375.68	
	Mixer	5.6	8744	39173.12	
	Mixer	5.6	8728	39101.44	
	Pump	22	1273	22404.8	
	Pump	22	5088	89548.8	
	Pump	22	3645	64152	
	Pump	2.5	16	32	
	Pump	0.18	279	40.18	
	Pump	0.18	8706	1253.66	
	Pump	0.18	8480	1221.12	
	Pump	1.2	8685	8337.6	
					346880.56
Filtering					
	Blower	51	3	122.4	
	Pump	1.2	8744	8394.24	
	Pump	1.2	8743	8393.28	
	Pump	37	136	4025.6	
	Pump	37	151	4469.6	
	Pump	37	156	4617.6	
	Pump	1.2	6723	6454.08	
					36476.8

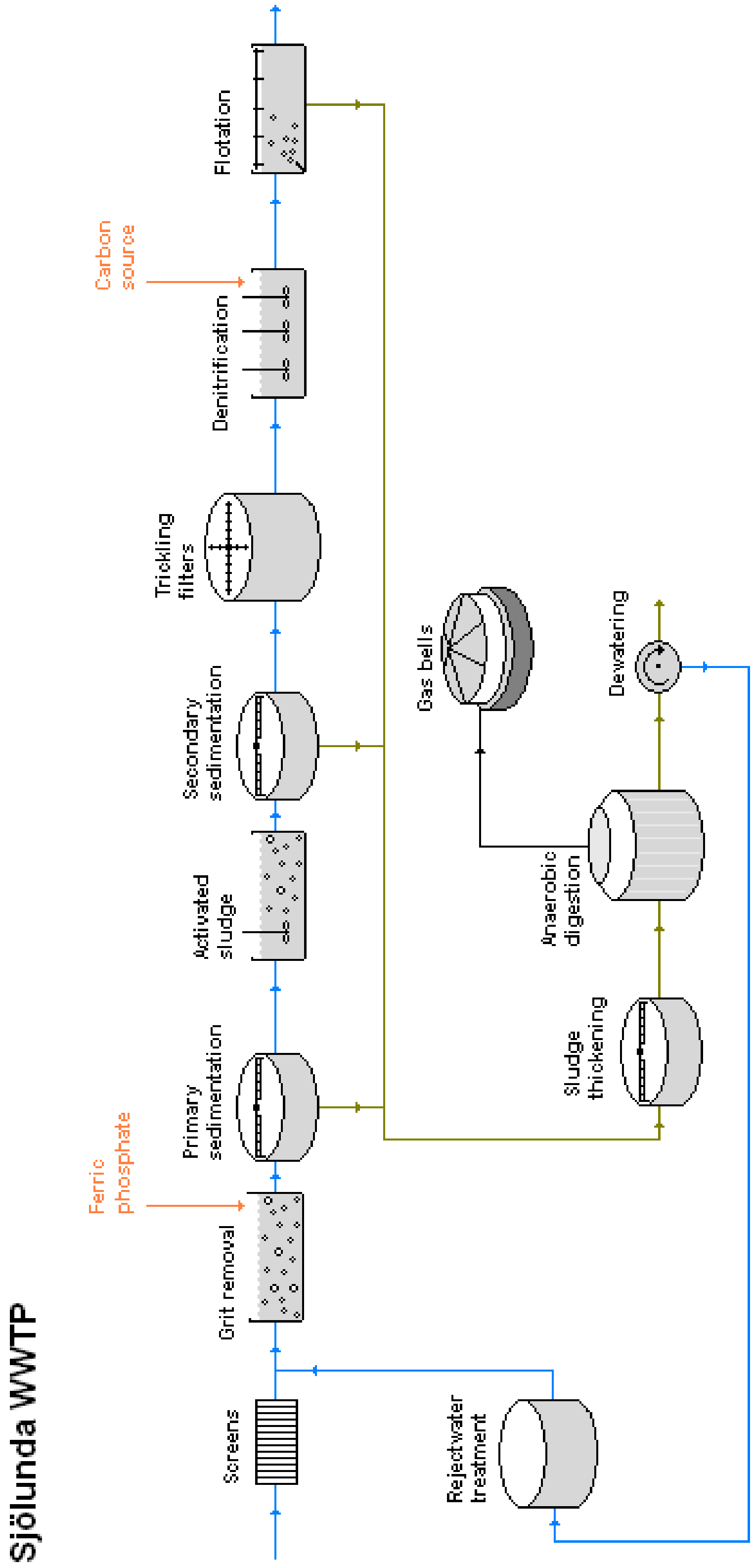
Sludge thickening					
	Mixer	0.26	8744	1818.75	
	Mixer	0.26	8740	1817.92	
	Pump	11	1167	10269.6	
	Pump	11	1273	11202.4	
					25108.67
Anaerobic digestion					
	Compressor	11	1518	13358.4	
	Compressor	37	2712	80275.2	
	Pump	11	8424	74131.2	
	Pump	11	950	8360	
	Pump	11	8116	71420.8	
					247545.6
Sludge dewatering					
	Centrifuge	22.5	2717	48906	
	Centrifuge	22.5	2173	39114	
	Mixer	1.5	906	1087.2	
	Pump	4	2451	7843.2	
	Pump	4	2114	6764.8	
	Pump	2.2	387	681.12	
	Pump	1.1	2117	1862.96	
	Pump	1.1	2652	2333.76	
	Screw	0.25	86	17.2	
	Transporter	18.5	73	1080.4	
	Transporter	3	58	139.2	
	Transporter	3	69	165.6	
	Transporter	11	59	519.2	
	Transporter	3	58	139.2	
	Transporter	1.1	2719	2392.72	
	Transporter	4	4805	15376	
	Transporter	3	58	139.2	
	Transporter	4	4805	15376	
					143937.76
Miscellaneous					
	Air dryer	3.6	8751	25202.88	
	Air dryer	3.6	8753	25208.64	
	Compressor	18.5	4334	64143.2	
	Compressor	18.5	4406	65208.8	
	Compressor	12	369	3542.4	
	Gas furnace	10	2351	18808	
	Pump	16	63	806.4	
	Pump	16	74	947.2	
	Pump	1.5	8754	10504.8	
	Pump	4.3	8744	30079.36	
	Pump	0.84	8011	5383.39	
					249835.07

1. run-time during 2005

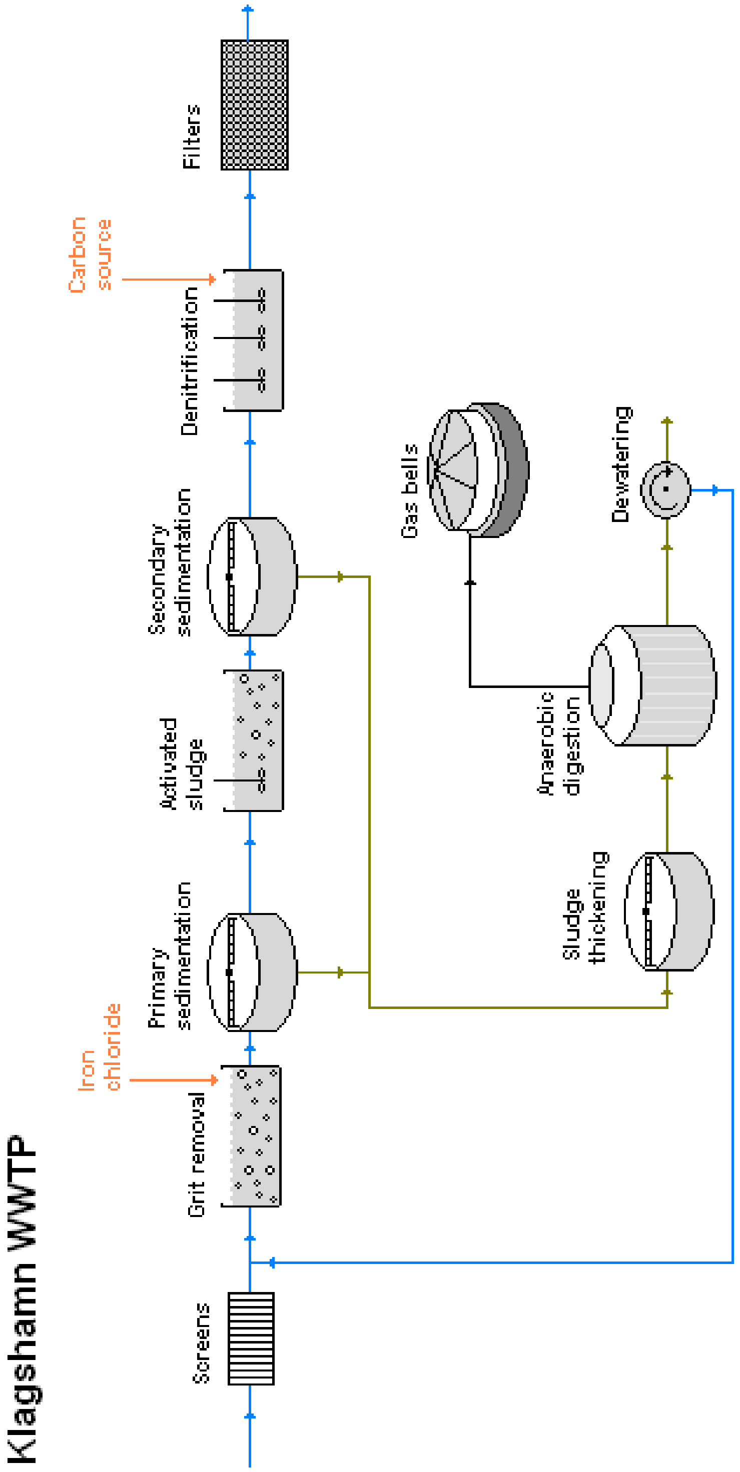
2. Based on run-time*rate power*0.8

3. The blowers are shared between the grit removal and the activated sludge. The energy used by each process was assumed to be proportional to the air flow

Appendix C - Schematic picture Sjölunda WWTP



Appendix D – Schematic picture Klagshamn WWTP



Appendix E - Calculations

Sjölunda – Activated sludge

There are four parallel lines: G1, G2, G3 and G4. For G1-G3 the energy usage is monitored, both for the whole lines and for the blowers. G4 is measured only together with other processes, by two different meters. The values for G1-G3 has been used to estimate the consumption of G4.

The wastewater is lifted into G4. The energy used by the pumps for doing so is calculated by:

$$E = \frac{Height \cdot Density \cdot 1\, m^3 \cdot g}{Efficiency}$$

and:

$$Energy\ during\ one\ year = E \cdot Flow_{Year}$$

To get the answer from the second equation in Wh, the answer must be divided with 3600, else the answer will be in J.

The two formulas combined with values inserted:

$$\frac{5.87\, m \cdot 1000\, kg/m^3 \cdot 1\, m^3 \cdot 9.82\, m/s^2}{0.6} = 96072\, J \Rightarrow$$
$$\Rightarrow 96072\, J \cdot 18141889\, m^3/year = 476987\, kWh/year$$

To get the energy consumption of the blowers in G4, the influent flow rate and the amount of air required are assumed to be proportional, by the same proportions in G1-G3 and G4.

$$Energy_{G4} = \frac{Energy_{G1-G3}}{Flow_{G1-G3}} \cdot Flow_{G4} =$$
$$= \frac{1724618\, kWh}{17685428\, m^3} \cdot 18141889\, m^3 = 1769130\, kWh$$

To get the energy consumption of the waste activated sludge pumps Hazen-Williams formula is used to convert a pipe length into a corresponding lift height.

$$h=6.05\frac{L}{D^{4.87}}\cdot\left(\frac{Q}{C}\right)^{1.85}$$

With the measured and collected data inserted the answer is:

$$h=6.05\cdot\frac{300\,m}{(250\,mm)^{4.87}}\cdot\left(\frac{834\,l/min}{140}\right)^{1.85}=0.1\,m$$

This is added to the lift height of the pumps, and the calculations are the same as for the inlet pumps.

The remaining calculations are based on estimated run-times and the rated power of the different objects.

$$Energy\,consumption=Runtime\cdot Rated\ power\cdot 0.8$$

The result from the formulas and the measured values from the power meters are added to give the total energy consumption of the activated sludge process.