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Industrial Electrical Engineering and Automation

Energy Conservation in Wastewater Treatment Operation

- A Case Study at Himmerfjärden WWTP

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A master thesis

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- a case study at Himmerfjärden WWTP

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Abstract

Swedish wastewater treatment plants' energy usage equals a total of 0.6 TWh per year. Together with the Swedish drinking water treatment, the usage corresponds to approximately 1% of the total electrical energy consumption in Sweden. Potentials for a reduction of this usage do exist. However, very modest efforts for energy usage conservation are attempted.

This thesis establishes a general methodology for performing an energy conservation project at any wastewater treatment plant. The methodology is then applied to an actual wastewater treatment plant, Himmerfjärden WWTP. Results when performing the energy conservation project and recommendations for future measures are presented.

The thesis clearly shows the existence of a potential for reducing energy usage in wastewater treatment operation, not necessarily implying a negative impact on the quality of the process.

Preface

This master thesis concludes our studies at Lund Institute of Technology (LTH), Lund University, for a master degree in mechanical engineering. The thesis has been worked out in cooperation with the Department of Electrical Engineering and Automation (IEA) at LTH and SYVAB.

There are a number of persons we would like to thank. First of all, our tutor Dr Christian Rosén at IEA, for indispensable guidance and for interesting discussions regarding the work with this thesis. Thanks also to Professor Emeritus Gustaf Olsson for being such a source of inspiration and motivation.

We would also like to thank the personnel at SYVAB and Himmerfjärden WWTP, for their interest in our work. Most of all, a large thank to Process Manager Malin Brännkärr for providing valuable information whenever needed.

Lund, 31 March 2006

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1 Introduction

1.1 Background

The most important goal in wastewater treatment is to fulfil the demands stated by the government concerning the effluent water quality to ensure the environmental wellbeing.

The second most important goal is to perform the required wastewater treatment as cost effective as possible; for the sake of the taxpayers as well as for the nature in form of reduced energy usage deriving from e.g. fossil fuel. Due to the fact that Sweden is becoming increasingly integrated with the rest of Europe and due to the now deregulated Swedish electricity market, the previously low Swedish electrical energy prices will most likely level out on a higher and more Europe-standard level. Naturally, this increases the financial benefits of reduced electrical costs even more in the future.

Swedish WWTPs use electricity corresponding to approximately 100 kWh per year and person equivalent (pe). This equals a total electricity consumption of 0.6 TWh per year. Together, the Swedish plants for wastewater and drinking water treatment corresponds to roughly 1% of the total electricity consumption in Sweden. (Wiberg 2006)

Compared to German WWTPs, Swedish plants consume twice as much electricity. Though the average German WWTP is larger than its Swedish equivalent, this indicates a great potential for a more effective electricity usage at Swedish WWTPs. Especially, considering official statements saying that German plants has a potential of reducing their electricity usage by 35%. (Kjellén, Andersson 2002)

1.2 Objectives

The main objective of this master thesis is to present an energy management plan for Himmerfjärden WWTP. Facts, ideas and discussions presented should lead to a considerable energy conservation and thus, noticeable financial savings.

A second objective is to present a general methodology of how to reduce the costs related to electrical usage at any WWTP. This methodology will then constitute the basis when performing the energy conservation project at Himmerfjärden WWTP.

The cost of the electrical use consists of different fees based on energy use and power demand respectively (further described in chapter 4.1 and 6.1). Hence there are two main questions related to reducing the total electrical cost:

- Is it possible to reduce the cost associated with energy use?
- Is it possible to reduce the cost associated with the power demand?

However, another very important objective of this thesis is to work as an eye-opener. Excessive energy usage due to inefficient treatment methods and a somewhat old-fashioned way to look at the energy aspect is a problem when dealing with today's energy situation. Energy is no longer a product that can be spent lavishly without circumspection, but should be considered as a product acting as a load, both from an economical and an environmental point of view.

Hence, conducting an energy conservation project is not only essential because of the obvious economical advantages it may entail, but also because of the environmental issues. Potentials for a more energy efficient wastewater treatment definitely exist, and should thus be aimed at.

1.3 Delimitation

Being an iterative process, an energy conservation project can go on for a considerable time. Hence, a large delimitation of this master thesis has been the time limit of the project. Another delimitation has been that the methodology is only implemented at one WWTP.

1.4 Target group

This master thesis is written so that all of the personnel at any WWTP should be able to follow most of the facts and discussions presented with the exception of some parts, where more special qualifications are necessary. People not familiar with water treatment, but with an education involving energy, chemistry, economics etc. should also be able to comprehend the main part of the discussions.

1.5 Methodology

Due to the authors' total inexperience in the wastewater treatment area, the very initial measure was to perform an extensive literature study in an attempt to somewhat comprehend the complex nature of wastewater treatment. This literature study has then been a never-ending task during the project time, since one can never be fully educated within the subject. Furthermore, a study in the

Matlab/Simulink environment was performed to be able to handle the computer model simulations used.

The results and recommendations presented in this thesis are mainly consequences of knowledge assimilated when performing the literature study. However, many of the theories and the consequent results presented are based on thoughts and ideas born when brainstorming and discussing the questions raised, both within the project task group and with other educated people.

Furthermore, to be able to verify the appropriateness of the suggested measures, a large amount of time has been spent calibrating the computer simulation model to fit the conditions at Himmerfjärden WWTP. When calibrated, the model has been a useful and powerful tool.

1.6 Outline of the thesis

This master thesis begins with an introduction chapter, where the administrative parts of the project are presented. In chapter 2, the necessity of wastewater treatment is motivated and the most common parts of the wastewater treatment process are described.

After the treatment introduction in chapter 2, chapter 3 treats the specific situation at Himmerfjärden WWTP. The company responsible for Himmerfjärden WWTP is briefly presented, after which the specific wastewater treatment implemented at Himmerfjärden WWTP is described.

Chapter 4 continues with considering the different steps of the general treatment process from an energy viewpoint. Here, an introduction to the electrical agreement between a WWTP and its electrical energy supplier is presented. Chapter 4 also describes the different treatment components, i.e. energy consumers such as pumps and compressors as well as potential energy contributors.

With the basics of wastewater treatment explained, chapter 5 treats one of the objectives of this master thesis; a general methodology for reducing the costs related to electrical usage. In chapter 6, the methodology worked out in chapter 5 is implemented at an existing WWTP, i.e. Himmerfjärden WWTP. Simple financial calculations, specific to the situation at Himmerfjärden WWTP, are also presented in this chapter.

Chapter 7 summarises the conclusions and results of this master thesis and also brings up questions for future work related to energy reduction at Himmerfjärden WWTP.

2 The wastewater treatment process

This chapter starts with explaining why the very existence of WWTPs is necessary. The contents of wastewater are then described, after which the most common treatment processes are presented.

2.1 The necessity of wastewater treatment

The need for wastewater treatment grows with increased use of water and the subsequent increase in wastewater volume. The public health and the environmental wellbeing are naturally of vast importance and dependent on a proper treatment of the wastewater, a treatment that results in a low negative effect on the effluent recipient. This treatment should include removal of hazardous materials, suspended solids and organic oxygen demanding substances that consume the oxygen that is a requisite for the natural aquatic life in the recipient.

The importance of wastewater treatment first became evident with the outbreak of cholera in some large Asian and European cities during the early 19th century. Some years later, in London, a connection between the outbreak of the disease and the handling of untreated wastewater was established which resulted in a totally different way of looking at wastewater handling. Instead of just being thrown into the street after use, the wastewater was now transported by pipes or channels away from the populous areas. (Ingildsen, Olsson 2001)

The industrialisation later led to new problems. An increased use of water meant a larger impact on the recipient and hence the entire environment. Soon it became obvious that something had to be done to protect the environment from further and increased pollution caused by human activity. (Ingildsen, Olsson 2001)

One of the largest threats posed by insufficient wastewater treatment is eutrophication. This is the result of when a body of water contains high concentrations of the nutrients phosphorous and nitrate. The high amounts of accessible nutrients cause excessive growth of algae. Later, the dead algae decompose and this causes an insufficiency of oxygen. When the oxygen level drops below 2-4 mg/l the affected aquatic life cannot survive and starts to abandon the area or dies. Furthermore, nitrogen in the form of ammonia, mainly originating from urine, is very toxic and can kill fish even in quite small concentrations. (Ingildsen, Olsson 2001)

In contrast to the negative effects of nutrient abundance, e.g. nitrogen and phosphorous, nutrients are also a prerequisite for all life. Especially nitrogen and phosphorous are of such importance that they are called growth-limiting substances and are often the controlling factors in nature, serving to limit growth. (Ingildsen, Olsson 2001)

As of today toxic chemical substances, heavy metals, e.g. cadmium and mercury, and other complex organic compounds, e.g. PCB, are hard to treat and are deposited back into nature via the WWTP effluent or sludge disposal. This is a problem yet waiting for a solution. (Ingildsen, Olsson 2001)

2.2 Wastewater composition

The amount of different wastewater pollutions arriving at a WWTP varies between different plants, due to differences in load. Community character, amount of industries connected to the WWTP, amount of rainwater leaking into the tunnels etc. are reasons for this. Furthermore, a time-dependent difference in load can also be found due to varying public and industrial activity.

Pollutions in the wastewater can be classified with respect to particle size, either as suspended or dissolved particles. Another method often used is to classify the pollutions as either organic or non-organic matter. In addition to these substances, suspended solids are also found.

2.2.1 Suspended solids

Suspended solids found in the wastewater are often removed in connection to the inlet. This process is further described in chapter 2.3.1. The removed material are deposited or incinerated.

2.2.2 Organic matter

Organic matter is made up of carbon, oxygen and hydrogen. Nitrogen, phosphorous and other molecules may also be attached. Thousands of different types of organic material can be found in the wastewater. Organic matter is used in the treatment process and is essential in the nitrification process. However, removal of the organic matter is a necessity to avoid oxygen reduction in the effluent recipient.

Due to the diversity of the organic material it is difficult to use a direct measurement to determine the amount of organic material in the wastewater. Instead, the amount of oxygen used for degradation of the organic material is measured. This method not only gives the advantage of being an efficient method for determination of the organic content. It also provides information about the amount of oxygen needed in the treatment process for removal of the organic material.

Organic material is usually measured in means of BOD or COD. BOD, or Biological Oxygen Demand, is a measurement of the amount of oxygen required to biologically degrade the organic material. The degradation is carried out by microorganisms consuming oxygen. The BOD value is a measurement of the amount of oxygen consumed by the microorganisms during a five-day period (BOD_5) or a seven-day period (BOD_7). (Ingildsen, Olsson 2001)

COD, or Chemical Oxygen Demand, determines the amount of organic material that can be degraded by chemical oxidation. Normally potassium dichromate ($K_2Cr_2O_7$) is added to the sample. The amount of organic material is estimated by measuring the consumption of the chemical oxidiser. This method of estimating the organic content is faster and more accurate than the BOD analysis. (Ingildsen, Olsson 2001)

2.2.3 Non-organic matter

Non-organic matter in the wastewater almost exclusively consists of dissolved salts. These salts have no or very limited effect on the effluent and are hence not subject for further treatment. Instead, current treatment processes of non-organic matter fully concentrate on the reduction of nitrogen, phosphorus and heavy metals. (Kemira 1989)

Nitrogen and phosphorus are nutrients that can cause eutrophication in the effluent, with a growth of organic substances, e.g. algae, as result. When these organic substances later die and decompose, oxygen is required. Consequently, eutrophication causes an oxygen reduction in the effluent. Hence, it is important to remove these nutrients. As mentioned earlier, nitrogen in the form of ammonia is toxic and even low concentrations can be lethal for the aquatic life in the effluent. When arriving at the WWTP, most nitrogen is in the form of ammonium. The rest is bound to organic matter, and is released as ammonium when the organic matter is degraded. Besides the fact that ammonium acts like a nutrient and hence causes eutrophication, ammonium causes oxygen consumption due to oxidation. Nitrogen oxidising bacteria transform ammonium to nitrate under heavy oxygen consumption, according to the formula (Kemira 1989)

$$\mathrm{NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O.} \qquad (2.1)$$

This oxidation process is called nitrification. The oxygen demand during this process amounts to almost five times the ammonium content. Hence, it is important to reduce the amounts of ammonium in the wastewater before reaching the effluent. A few approaches to this exist, and will be presented later in this chapter.

2.3 Wastewater treatment

As discussed earlier, wastewater consists of different types of matter. All the different matter requires different methods for removal. Several methods for removal exist, and the most common ones will be discussed in this chapter.

2.3.1 Mechanical treatment

Mechanical treatment is the simplest form of wastewater treatment. The first step is to remove larger pollutants such as solid materials, e.g. plastics and fabrics. This is carried out by letting the wastewater pass a screen or a sieve, where larger objects are trapped. In addition to this, further removal of suspended particles, such as sand and coffee grounds, is achieved by letting the wastewater pass a sand trap. A reduction of the flow velocity causes heavier particles to sink to the basin floor. The sand trap may be aerated, to keep the water aerobe and to simplify grease removal.

Further mechanical treatment involves letting the wastewater settle in a basin, allowing smaller particles sink to the basin floor creating sludge. This sludge, referred to as primary sludge, is removed from the basin floor by scrapes and transported to further sludge treatment.

The mechanical treatment processes only remove about one third of the oxygen consuming pollutants. Furthermore, none of the nitrogen and phosphorus content is removed. Hence, mechanical treatment solely is not an adequate treatment method, and requires further treatment methods. Mechanical treatment is hence considered to be only a preliminary wastewater treatment method.

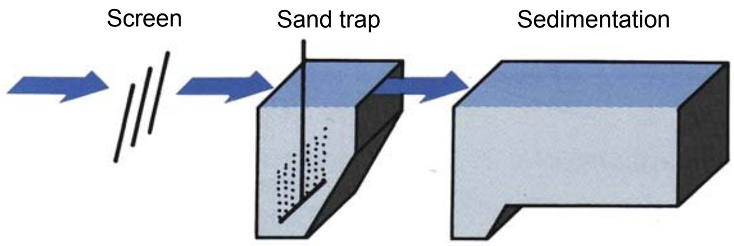

Figure 2-1 Example of mechanical treatment with a screen, an aerated sand trap and settling. (Kemira 1989)

2.3.2 Biological treatment

The biological treatment is carried out by microorganisms, mainly bacteria, degrading the organic matter. The degraded matter is then bound into flock particles and separated from the water by settling, thus creating sludge. The biological degradation can occur under both aerobic and anaerobic conditions. (Ingildsen, Olsson 2001)

Under anaerobic conditions, no oxygen is present in the process causing some microorganisms to use nitrate as their oxidiser. The organic substances are oxidised into carbon dioxide and water, while some part of the matter is degraded into methane gas. Anaerobic conditions in the biological treatment process are normally used only when treating heavily polluted wastewater, and as a stabilising process, i.e. anaerobic digestion. (Kemira 1989)

Under aerobic conditions oxygen is present in the process. The organic material is oxidised into mainly carbon dioxide and water. Some part of the organic material is used for growth of the bacteria. Biological treatment during aerobic conditions is usually performed as either fixed film process or activated sludge process. (Kemira 1989)

Biological treatment using the fixed film process is carried out by letting the wastewater pass through a material, which is oxygenised. A culture of microorganisms grows on the material, consuming the organic matter in the wastewater. When the layer of microorganisms on the substrate grows thicker, the wastewater transports the microorganisms to the effluent. The microorganisms are then separated from the wastewater by an adjacent settler creating sludge. (Kemira 1989)

Biological treatment using the activated sludge process involves keeping the sludge, containing microorganisms, active and suspended in the basin. This is performed by letting an aeration device constantly provide the wastewater in the basin with oxygen. When oxygen is present, the microorganisms in the activated sludge consume dissolved organic matter and colloidal particles. To achieve an adequate degrading speed the concentration of microorganisms in the basin must be at a certain level. This is accomplished by recycling the main part of the sludge. Only a minor part of the sludge, equivalent to the continuously produced sludge, is separated and removed from the process as surplus sludge. (Kemira 1989)

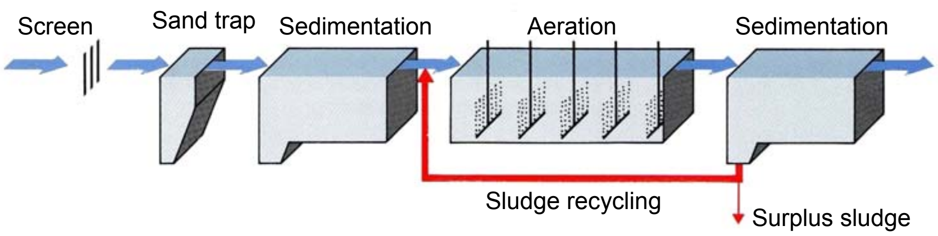

Figure 2-2 Biological treatment using the activated sludge process with sludge recycling. (Kemira 1989)

2.3.3 Nitrogen removal

Nitrogen removal is performed by nitrification and denitrification respectively. During the nitrification process, nitrogen in the form of ammonia is oxidised into nitrate according to formula 2.1. The process is performed by microorganisms called nitrifiers consuming oxygen. Hence, the nitrification process is usually performed in the same basin as the biological treatment. (Kemira 1989)

The denitrification is performed by microorganisms called denitrifiers. This is the same type of organisms that use oxygen to oxidise organic matter during aerobic conditions. However, during anoxic conditions where no oxygen is present, the microorganisms transform nitrate into free nitrogen, carbon dioxide and increased body mass. The denitrification occurs according to the formula (Kemira 1989)

$$2NO_3^- + H^+ + \text{Organic substance} \rightarrow N_2 + HCO_3^- . \qquad (2.2)$$

Since the nitrification and denitrification occur during aerobic and anoxic conditions respectively, the processes cannot occur at the same time. Hence, WWTPs are designed to allow these processes to occur either at different places or at different times. The most intuitive method of performing the nitrogen removal would be to first perform the nitrification to form nitrate and then to perform the denitrification to remove it. However, the denitrification process requires an organic substance, according to formula 2.2. Hence, it should be more convenient to perform the denitrification prior to performing the nitrification, since organic matter at that time is present. This somewhat paradox situation has a few approaches. The most common way is to perform the nitrogen removal by starting with an anoxic zone and hence denitrification. When reaching the subsequent aerobic zone, the water is nitrified. By recirculating the nitrified water to the anoxic zone the denitrification can be performed. The advantage using this method is that the wastewater provides the organic matter. Hence, no external organic source is needed. (Kemira 1989)

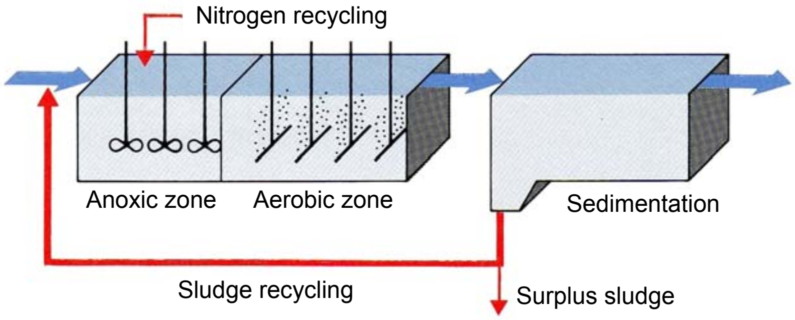

Figure 2-3 Nitrogen removal using pre-denitrification. (Kemira 1989)

Another approach is to add an external source of organic matter, e.g. ethanol, methanol, acetic acid or farina, to the denitrification process. The denitrification process is then consequently no longer dependent on the biological matter provided by the wastewater. Hence, the denitrification can follow the nitrification, causing a situation where recirculation of the wastewater is no longer necessary. (Kemira 1989)

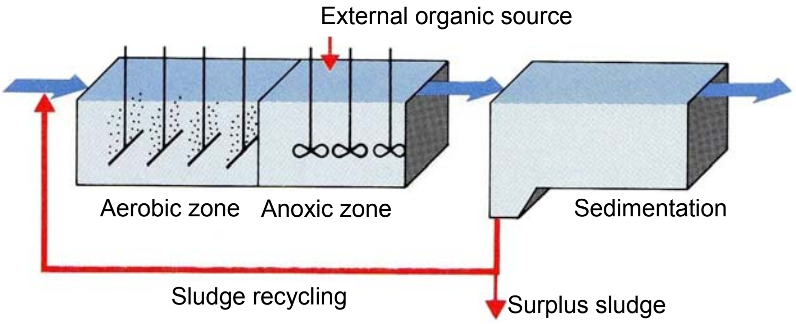

Figure 2-4 Nitrogen removal by nitrification followed by denitrification. (Kemira 1989)

Further methods involve alternating the state of the reactor, between aerobic and anoxic conditions, or to combine aerobic and anoxic conditions in the same reactor.

2.3.4 Phosphorus removal

Removal of phosphorus can be achieved by either a chemical process or a biological process. The chemical process is rather simple and involves adding metal ions, e.g. aluminium sulphate and iron chloride, to the wastewater. The phosphate and the metal ion added form a metal phosphate molecule, which coagulates to form small particles. The particles join together in larger clusters called flocs, which can be separated from the wastewater by sedimentation. (Ingildsen, Olsson 2001)

Biological phosphorus removal is a far more complex process. The process is based on a group of bacteria called PAO - Phosphorus Accumulating Organisms. The phosphorus accumulation takes place in two steps, firstly an anaerobic step and secondly an aerobic step. During the anaerobic step, the PAOs store a special organic compound called VFA - Volatile Fatty Acids. These bacteria store the organic matter as PHA - polyhydroxyalkanoates. In the second step, the PHAs are degraded for respiration and growth. At the same time, phosphate is assimilated into the cells. The polyphosphate storage in the cells is hence increased. The actual phosphorus removal occurs when the sludge containing the accumulated phosphorus is removed. (Ingildsen, Olsson 2001)

2.3.5 Sludge treatment

Sludge is a by-product produced by several processes in the wastewater treatment. Sludge is produced by growth of microorganisms, precipitation and separation of suspended solids in the wastewater. Sludge is considered to be a waste product, but is also essential in the treatment process. Sludge treatment often involves dewatering, drying, incineration and usage as landfill. Since sludge contains large amounts of nutrients it is also often used as fertiliser. However, sludge also contains toxic substances such as mercury and lead, which are difficult to remove. Hence, sludge usage as fertilizer is often questioned. (Ingildsen, Olsson 2001)

3 Himmerfjärden WWTP

This chapter briefly presents the company responsible for the operation at Himmerfjärden WWTP. The wastewater flow including the different treatment processes at Himmerfjärden WWTP is also presented.

3.1 Company presentation

SYVAB is a municipal joint stock company with six municipal owners; Botkyrka, Huddinge, Salem, Stockholm, Nykvarn and Södertälje. SYVAB Himmerfjärden WWTP serves the main part of the population in Botkyrka, Salem, Nykvarn and Södertälje together with parts of Huddinge and Stockholm.

The Himmerfjärden treatment plant is located by the northern shores of Himmerfjärden, south of Stockholm, in Botkyrka municipality. A total of 250,000 persons are connected to the treatment plant. In addition to this, several industries are also connected to the WWTP, e.g. Tumba Bruk and Spendrups brewery, representing a load of 35,000 pe. Today the average influent flow to the treatment plant is 100,000 m^3 of wastewater per day, and the maximum flow that can be treated is 130,000 m^3 of wastewater per day.

The purpose of the WWTP is to purify the wastewater mainly from suspended solids and materials that can be dangerous to the environment. Such materials are oxygen demanding organic materials, nitrogen and phosphorous.

The treatment plant was built during 1970-1973 and is a conventional Swedish WWTP with mechanical, chemical and biological treatment. (SYVAB 2005)

3.2 The wastewater flow

As mentioned in the previous chapter, many systems and solutions exist for performing wastewater treatment. Depending on the characteristics of the influent flow such as the size of the influent flow, concentrations of the different influent constituents etc., different solutions are more or less suitable. The following text in this chapter presents the method of wastewater treatment at Himmerfjärden WWTP, starting with an overview sketch in figure 3-1 of the wastewater flow. (SYVAB 2005)

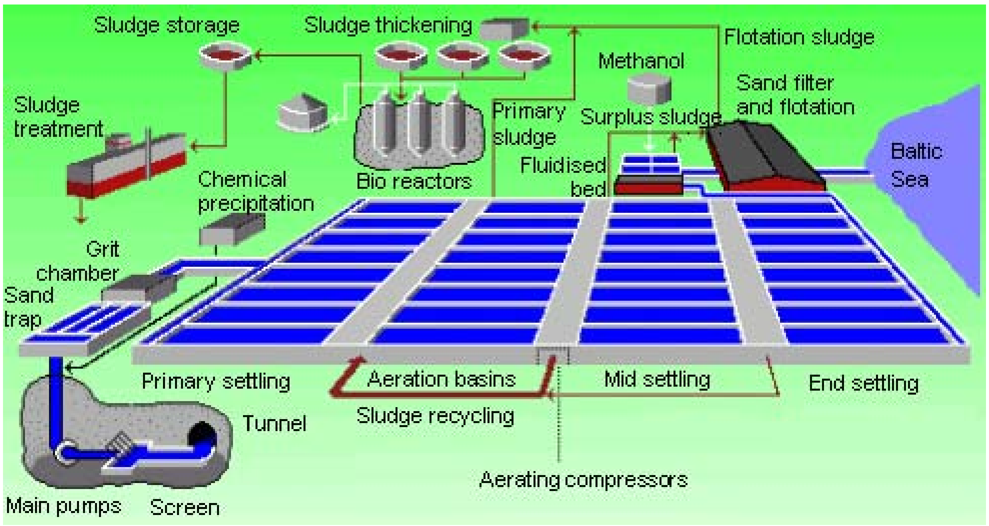

Figure 3-1 Explanatory sketch of the flow at Himmerfjärden WWTP. (SYVAB 2005)

3.2.1 The tunnel system

Since the largest concentrations of population is more than 30 km away from the treatment plant, there is a need for a well-developed tunnel system that can transport the wastewater all the way from the source to the treatment plant. This transport is mostly achieved by the gravitational force, but at some locations supplementary pumping is required. The total length of the tunnel system is 55 km.

In the tunnel, biological reactions are constantly occurring. Microorganisms in the sludge consume carbon and, since there is almost no oxygen in the wastewater, nitrate. The result of this is that hazardous sludge digestion gases, i.e. methane and hydrogen sulphide, are produced. To make sure none of these gases leak to the surroundings, fans are installed to secure a negative pressure inside the tunnel.

3.2.2 Inlet and main pump station

As described above, the wastewater arrives at the Himmerfjärden WWTP at the wastewater tunnel inlet located 54 meters below ground level. From here the water is subjected to the main part of the mechanical treatment, where larger objects are removed. Firstly, the wastewater enters the screening room, where objects larger than 20 mm are removed. If not removed, these larger objects would damage the following pumps and other technical equipment. The removed material is pushed up with compressed air to ground level, where it eventually is transported to the municipal waste deposit. As an example, during the year of 2004, the weight of removed sanitary towels, condoms, panty liners, q-tips etc. totalled 655 tons. (SYVAB 2004)

After the screens, between the different mechanical treatment devices, the water is subjected to a chemical treatment; ferrous sulphate is added to the water as a precipitation substance. This transforms the dissolved phosphorous in the wastewater to solid phase, making it easy to separate later in the process. The water is then pumped to ground level, where the mechanical treatment continues.

3.2.3 Sand trap and grit chambers

On ground level, the water passes a sand trap, which removes sand and other heavy particulate matters.

In the following grit chambers, objects larger than 2 mm are removed. As with the screens, this is to prevent damage and clogging in the smaller pumps and other technical components further down the treatment process.

3.2.4 Primary settling

Here, smaller particles sink to the basin floor, creating what is called the primary sludge. This sludge consists of approximately 50% of the solid organic pollution coming into the plant as well as 50% of the phosphorous amount in the wastewater. Sludge collectors scrape the settled solids to a hopper in the basin floor below the inlet, from where it is transported to the sludge treatment, further described in chapter 3.2.11.

3.2.5 Aeration process

Leaving the primary settlers, the water has now been mechanically and partly chemically purified. The next step in the wastewater treatment is based on biological reactions, where the purification proceeds with the help of microorganisms and bacteria.

The sludge in the aeration basins is called activated sludge and contains microorganisms. These organisms feed on organic substances, reducing the amount of organic constituents in the wastewater. Additionally, bacteria transform ammonium, mainly originating from urine, into nitrate. This transformation is called nitrification and is a vital process for further purification.

To be able to perform the reduction and transformation described above, it is, as mentioned earlier, necessary for the bacteria and microorganisms to have access to oxygen. Hence, there is a great number of aerating disc valves with rubber membranes positioned on the basin floor, evenly distributing tiny, finely scattered air bubbles for an optimal transfer of oxygen. The air is supplied from individually controllable hi-capacity compressors, supposed to produce an airflow corresponding to the amount of BOD in the inlet of the aeration basins.

3.2.6 Secondary and final settling

In these basins, the activated sludge from the aeration section sinks to the basin floor and is collected by floor scrapers. Most or all of the gathered sludge is recycled to the aeration basins, depending on the amounts of microorganisms and bacteria needed in the aeration process. If there are sufficient amounts of activated sludge in the aeration basins, redundant sludge in the secondary settling is pumped to the flotation tanks, further described in chapter 3.2.9.

3.2.7 Fluidised bed

After the secondary and final settling, the wastewater is pumped up through the floor of the fluidised bed, initiating the denitrification process. The upward streams of wastewater cause billions of tiny sand particles to float freely in the tank, maximizing the free sand surface area. Sticking onto this area, bacteria transform the nitrate into nitrogen gas, which floats up to the surface of the fluidised bed and is released into the atmosphere.

Energy is necessary for the bacteria to perform the transformation. Adding organic substances in form of methanol provides this energy, as described in formula 2.2. The methanol serves as food for the bacteria, enabling these to perform the denitrification.

3.2.8 Sand filter

The sand filter consists of three different filtering layers with the roughest material at the bottom and fine sand at the top. The filter is 70 centimetres thick and removes the last particles in the wastewater. These particles are regularly washed away to the flotation facility.

3.2.9 Flotation

This process can be regarded as the opposite to a settling process. Instead of sinking, the unwanted particles are brought to the surface. Air-saturated water is pumped into the flotation basins, mixing with the wastewater. When mixed, tiny air bubbles are released from the air-saturated water. Impurities get stuck onto these bubbles, which float up to surface, resulting in a layer of surface sludge. This sludge is removed from the surface and is pumped to the sludge treatment.

3.2.10 Outlet

The purified water is led 1,600 meters out into Himmerfjärden and is released into the Baltic Sea at a depth of 25 metres. During summertime the purified water is naturally spread out at the temperature shift at a depth of approximately 15 metres. The rest of the year, though, it floats up to the surface. The travel time for the wastewater from inlet to outlet at the Himmerfjärden WWTP is approximately 20 hours.

3.2.11 Sludge treatment

Sludge is pumped from the different basins in the process into the thickening tanks. Here, the sludge is thickened to a dry substance percentage of approximately 4%. After the thickening the sludge is anaerobically treated in bioreactors for production and extraction of digester gases. This treatment occurs at a temperature of 37 °C, to achieve sludge free from infectious matter. The extracted digester gases are used for heating the bioreactors as well as the WWTP facilities and the sludge drier.

From the bioreactors the treated sludge is pumped via the sludge storage to the sludge treatment facility. Here, the sludge is dewatered, first in centrifuges to a dry substance (DS) amount of approximately 27% and then in the sludge drier, to a DS amount of 80-90%. The separated water is recycled to the flotation.

The treated sludge, the so-called bio soil, is used when founding golf courses, noise reduction walls or for agricultural nutrition purposes.

3.3 Treatment result

When reaching the effluent, the levels of organic matter (BOD) in the wastewater are reduced by approximately 97%. Furthermore, nitrogen and phosphorus levels are reduced by 90% and 95% respectively.

4 Energy basics

The purpose of this chapter is to describe the basics of energy in the interest of a WWTP. First, the structure and contents of the relatively complex electricity bill is explained. The second and main part of the chapter continues with an account of the process equipment at a WWTP from an energy viewpoint. Energy consuming equipment is described after which the potential internal and external energy contributors at a WWTP are illustrated.

4.1 Electricity costs

The rate structures applied to the specific customer have no direct effect on the electrical use. On the other hand, an understanding of the rate structure is essential in the pursuit for reduced electrical costs. There are many opportunities to save money just by understanding the rate structure on the current billing. Hence it is of great importance to have an understanding of the current agreement with the electric utility company. (Water Environment Federation 1997)

The billing for electric service can take many forms depending on the economic objectives and administrative concerns that are being addressed by the utility. WWTPs typically are subject to rather complex rate structures.

The cost of electrical usage is divided in several different parts. The most common charges and the ones to take into consideration are the customer charge, the energy charge and the power demand charge. The sizes of these different charges vary with different types of processes.

The customer charge is a fee structured to cover the administrative costs incurred for providing the customer with services like reading the meter and preparing the mailing bills. (Water Environment Federation 1997)

The energy charge is the charge for the actual amount of energy used by the customer measured in kilowatt-hours (kWh). Since there is a variation in energy demand, the power company sometimes chooses to assess different charges depending on if the electric use occurs during peak or off-peak periods. This is the power company's attempt to try to even out the electric use to avoid an unbalanced use of their facilities. Peak usage periods in Sweden generally occur in the coldest winter months and during daytime when the public activity is at the highest. Controlling the large loads in a way that usage during peak-periods is avoided will consequently reduce the energy charge if this type of agreement is made. (Water Environment Federation 1997)

The demand charge represents the maximum power consumed during the billing period, averaged during a continuous period. The demand charge is supposed to cover the costs for building the power plants, the transmission lines and other equipment that is needed to provide the customer with the power service. The energy use is integrated during a certain time, usually a 15-minute, 30-minute or one-hour period, and from this the average power is calculated. The demand charge is sometimes calculated by taking an average of the two largest loads during different months. By averaging the power demand, power spikes during in-rush currents, when starting a large load, are levelled out. Hence the power spikes have no effect on the demand charge. The demand rate is estimated in advance, and if the rate is exceeded the customer is obliged to pay a rather tangible penalty fee. It is therefore important to calculate an accurate power rate. If the rate is set too high, the demand charge will be unnecessarily high. But if the rate is set too low, the customer will probably have to pay a penalty fee as a result of excessive power use. (Water Environment Federation 1997)

4.2 Energy utilization

While it is of great importance to have an understanding of which parts in the wastewater treatment process that consume energy, it is difficult to present a general picture of how the energy utilization is divided at different WWTPs. Energy usage varies significantly depending on location, plant size, level of pollution of the wastewater, type of treatment and mode of operation. Generally, plants with a more advanced treatment require larger amounts of energy. The major energy consumers at most WWTPs are pumps, blowers, mechanical aerators and solids-handling systems. In this subchapter the most common energy utilization processes at a WWTP is described. (Water Environment Federation 1997)

4.2.1 Preliminary and primary treatment

Before the wastewater arrives at the WWTP it has to be transported through a tunnel system. As mentioned earlier, in cases where the wastewater is unable to move by the gravitational force, pumps must help transport the wastewater through the tunnel to the treatment plant. This can be a quite large energy consumer depending on the topographical conditions. As the wastewater in the tunnel is transported, biological reactions are constantly occurring. Hazardous gases are produced, which must be transported away from the tunnel due to safety reasons. Hence, large fans sometimes ventilate the tunnel system. These fans often consume a considerable amount of energy, and should be subject of further consideration.

When the wastewater arrives at the WWTP it is subjected to a screening process where large solids are removed. The screening bars must be cleaned to avoid clogging. This is either done manually or by electrically driven raking devices. The electrical equipment operating the rakes is often small, and most often not activated in a continuous manner. Instead, the difference in water level before and after the bars are measured, and the rakes are activated when the difference is large enough. By operating in this way, unnecessary activity of the rakes can be avoided. In some cases the screened material is grinded. This process can also be considered to be a minor energy consumer, since the grinder often is used in an intermittent manner and since the volume of the material to be grinded often is quite small. The total energy use in the screening process generally represents a minor portion of the total energy usage at a WWTP.

When the wastewater has been subjected to the preliminary treatment it has to be lifted to the level of the primary treatment. This is accomplished by the main pumps. These pumps generally represent 15-70% of a WWTP's total energy usage, depending on the elevation difference between the WWTP site and influent sewer. All the pumps in the entire collection system can represent as much as 90% of the total energy utilization.

When the wastewater has been elevated to the level of the treatment plant, it is often subjected to some sort of grit removal. The design of the grit removal varies between different WWTPs, but generally there are two types of grit removal; aerated and non-aerated. The non-aerated grit removal process consumes small amounts of energy. In aerated grit chambers the blowers use a considerable amount of energy and should consequently be subject of further revising.

In the primary treatment, settleable solids and floating materials are removed from the wastewater. The main energy consuming parts in this process are the primary sludge pumping, the collector mechanisms and floatable skimming handling, with the primary sludge pumping as the largest consumer.

Though representing a small energy consumption post, the screening and grit removal are highly necessary to remove any matter that could cause serious and expensive damage on the finer equipment further down the purification process.

4.2.2 Biological treatment

When the wastewater has passed the primary and preliminary treatment, it contains high amounts of organic matter. To reduce the amounts of organic material in the wastewater, numerous methods exist. These methods can, as mentioned earlier, generally be categorized as either suspended growth or fixed film processes. The fixed film process itself uses quite low amounts of energy, but requires recirculation of the treated wastewater. This recirculation can be an energy demanding process, and should be considered in an energy efficiency project. Additionally, the fixed film processes also tend to produce odours, and methods to reduce these odours can be energy demanding.

The suspended growth method involves keeping a culture of microorganisms active. These microorganisms need oxygen to survive. The oxygen demand can be met in many ways, but most aeration devices used can be categorized as either dispersed, diffused or mechanical aeration systems. Overall, the devices used for aeration represent a significant part of the total energy use at a WWTP, sometimes as much as 50%. Hence, the aeration process can, together with the main pumping, be considered as the most energy demanding process at a WWTP and should consequently undergo extensive investigation in case of an energy efficiency project.

The fixed film process is less energy demanding compared to the suspended growth method, but its reduction of organic substances is not as effective. With the often necessary odour removal process, the fixed film process uses almost as much energy as the suspended growth method.

Another energy demanding process is the activated sludge recycling. After the activated sludge process, the wastewater is led to a settler. In the settler, activated sludge sinks to the bottom and is recycled to the aeration basin. Return activated sludge rates are usually expressed as percentage of the influent flow, and typically range between 40 – 100% of the influent flow. As a result of the high recirculation rates, the pumps recycling the primary sludge from the settler to the aeration process use quite large amounts of energy and should hence be object of further investigation.

4.2.3 Additional wastewater treatment

In addition to the traditional treatment processes, more advanced methods sometimes are introduced to further enhance the effluent water quality.

Chemical treatment requires energy mainly in the feeding and mixing processes. Additional sludge pumping as a result of the chemical treatment requires large amounts of energy and is generally the largest energy consumer caused by chemical treatment. Other energy consumers include e.g. chemical feeding, mixing and other treatment of the chemical.

Historically, the removal of phosphorus from wastewater has been accomplished by chemical precipitation with metal salts. This method requires large amounts of energy mainly in sludge treatment and treatment of the chemicals. A more modern approach to the problem is usage of biological phosphorus removal where the organic organisms are placed in an anaerobic environment before they are put back into an oxidative environment. This approach requires an additional step in the treatment process, and additional energy is required in mixing the tank contents and keeping the organisms suspended in the anaerobic phase.

The biological nitrogen removal, accomplished by nitrification and denitrification, has different approaches. One way is to use a system where the anoxic zone is positioned in front of the aeration tank. Wastewater at the end of the aerated tank is recycled to the beginning of the tank, to the anoxic zone. However, this approach requires a high rate of recirculation if a high nitrogen removal rate is to be obtained. As an example, a 95% efficiency of the denitrification requires a total of 19 recirculations, and a large amount of energy in pumping processes is consequently required. (Water Environment Federation 1997)

An alternative approach is to use a separate denitrification tank. The nitrified water is led to a tank with anoxic conditions, where bacteria placed on small sand particles perform the denitrification. The sand particles must be kept in suspension in the tank for the denitrification to take place. An upward water flow must be kept fairly constant to keep the particles in suspension, and this may require an energy demanding recirculation of the water. In addition to this, an organic carbon source is required. Ethanol or methanol is often used, and this usage can create additional sludge and an increased energy usage in sludge treatment.

4.2.4 Sludge treatment

Throughout the treatment process, sludge is produced and utilized. The energy use related to the sludge treatment is generally found in the recycling and pumping processes, and in the stabilization and drying processes. Energy is required to pump sludge between different parts and processes at the WWTP. Sludge is either recycled or removed from the treatment process. Together, the sludge pumping processes usually consumes large amounts of energy.

When removed, the sludge may be treated. Numerous of different approaches exist, but the common goal of the treatment is to stabilize the sludge and decrease the sludge volume. The sludge dewatering is usually accomplished by settling. This process can be considered as energy efficient.

When the sludge has been dewatered it may be anaerobically or aerobically digested. The anaerobic digestion process is usually quite energy efficient and occurs at all temperatures between freezing point and boiling point. Higher temperatures provide more optimal conditions for methane production. Heating of the sludge is hence preferred, and this may be an energy demanding process depending on the method of heating. Other energy usage is found in the pumping and mixing processes.

Aerobic digestion can be considered to be very energy intensive and should be looked upon in case of an energy efficiency project. The method also produces a sludge that is more difficult and costly to dry.

Further sludge dewatering processes usually require large amounts of energy. Some sludge dewatering can be accomplished solely by energy efficient settling, but higher water removal rates require other more energy demanding processes. Generally, the energy use required increases exponentially with the desired water content of the sludge. Methods to reduce the water content of the sludge primary involve centrifuges and some form of incineration. The incineration process involves very high temperatures and hence a large amount of energy is required. This energy demand can be met by using the produced digester gas as an energy source. The centrifuges also require large energy amounts, but are driven by electrical motors.

4.2.5 Other energy consumers

A WWTP is usually a rather large complex with many auxiliary processes that require energy. Examples of miscellaneous processes that require energy are compressors for compressed air, water pumps, electrical motors, valves and heaters. Just as any type of building, WWTPs also require energy for space heating, ventilation and lighting equipment. All these processes have a part in the energy utilization, and avoidance of excessive energy usage in these processes is critical if the ambition is to reduce the total energy consumption.

4.3 Energy contributors

As explained earlier, WWTPs consume a lot of energy. But they also have access to substantial energy resources. The most evident energy contributor derives from the digester gas production. In addition, large amounts of heat energy are conserved in the wastewater. Other possibilities for internal energy generation are hydroelectric power, solar energy and, in a few cases, wind energy.

4.3.1 Digester gases

A high production of digester gases is one of the most important issues in achieving an optimal energy balance at a WWTP. Most of the sludge arriving in the bio tanks is primary sludge, which is collected in the primary settling. Hence, the time the wastewater spends in the primary settling basins is of great importance for how much digester gas fuel, i.e. organic dry substance, is added to the bioreactors. The gas production in the bioreactors can be altered by controlling the time the sludge is kept there and also by controlling the bioreactor temperature. As an example, a reduced digestion time from 30 to 15 days results in a reduced digester gas production by 10%. (Kjellén, Andersson 2002)

As mentioned above, the production of digester gases occurs in bioreactors, where the sludge is anaerobically treated. Under normal conditions, the digester gas consists of 60-70% methane, 30-40% carbon dioxide, 4% nitrogen and small amounts of oxygen (Kjellén, Andersson 2002). Additionally, there are traces of hydrogen sulphide, which cause the characteristic bad wastewater smell. It is these traces of hydrogen sulphide that limit the direct usage of the digester gases as an energy source in gas engines. According to Swedish regulations, the amount of hydrogen sulphide must be kept within certain limits for it to be allowed as an energy source for engines.

4.3.2 Wastewater heat energy

Heat energy stored in the wastewater can be extracted and used for heating the WWTP facilities as well as distributing heat to a possible local district-heating network. Naturally, the geographical aspect must be taken into consideration; a

WWTP situated far from urban areas or far from a district-heating network has limited possibilities for heat energy recycling.

Stored heat in the sludge and in the, not yet totally purified, wastewater is almost always necessary for the required biological activity. Hence, a possible heat extraction can only occur in the end of the treatment process, i.e. when the wastewater is purified. A favourable way to extract heat energy from the purified wastewater is to use heat pumps. The wastewater is a very suitable heat source because of the great volumes and the reliable steady flow. Additionally, during wintertime, the purified wastewater temperature can reach as high as 14 °C and seldom falls below 10 °C, thus representing a significant heat energy source. Additionally, it is suspected that a lower effluent temperature has environmental benefits; thermal stress on the outlet surroundings is reduced and the water quality increases.

At most WWTPs the effluent flow is of such proportions that most of the necessary heating, often extracted by combusting digester gases, could be extracted from the effluent instead. This could free most part of the produced digester gases to be used in other ways, further discussed in chapter 6.4.1.

4.3.3 Hydroelectric power

With the right elevation conditions, hydroelectric power can be an alternative energy source. A common hydroelectric power unit can generate energy with an efficiency of over 70% for most flows. For normal WWTP flows, a hydroelectric unit can generate a few kW for each meter of height of fall. (Kjellén, Andersson 2002)

4.3.4 Solar energy

Solar energy can be transformed to either heat energy or electricity. A necessary requirement for extracting solar energy is a large area of solar panels. Since most WWTPs cover a lot of ground, this requirement is often well met. Due to the simple shape of the WWTP facilities, the placing and the installation of solar panels are easily implemented. The big disadvantage is that solar panels are expensive to operate and maintain. Together with the fact that the annual amount of sun hours in Sweden is comparatively small, this results in an overall disadvantage to invest in solar panels. It should be taken into consideration, though, that the amount of sun hours in Sweden varies a lot depending on the location of the WWTP. Extraction of heat energy can produce 300-450 kWh per year and m^2, while transformation to electricity can produce 50-120 kWh per year and m^2. For a normal size WWTP, this can cover up to approximately 4% of the total electricity usage. (Kjellén, Andersson 2002)

4.3.5 Wind energy

Most WWTPs are placed at a low ground level, which is a large disadvantage when only considering the wind energy aspect. In some cases, though, the WWTP is situated right by the ocean and here wind energy can be an interesting alternative.

5 Energy management

In this chapter, a general methodology is presented of how to perform an energy saving project in a structured way. Developing an energy management plan does not have to be as complicated as it first may seem. A management plan can be set up fairly easily with five simple steps: collect data, analyse data, create a plan, implement the plan and evaluate the plan. The evaluation of a plan implementation should then lead back to the initiating step of data collection, making the whole energy management process highly iterative.

5.1 Collection of data

The main reason for working out an energy management plan is naturally to achieve financial savings. Thus, the first step in developing an energy management plan is to obtain an understanding of the structure of the current billing system; depending on the specific agreements of a specific power company contract different measures can be the optimal ones to implement. Discussion about how to treat the electricity agreement continues in the following subchapters.

After collecting the relevant specifics of the electrical agreement, the next step is to gather all necessary data related to the purification process. Naturally, this is the intuitive step and must be done to obtain a comprehensive view of how the energy utilization at the WWTP looks like. This is best accomplished by developing a list of the major energy consuming equipment. If information about energy usage is inadequate, the list can instead be based on the most power demanding equipment. The list should include information about the name of the equipment, where in the process the equipment is found, nameplate information such as motor power and revolutions per minute and a description of the operating time. Information whether it is of constant speed or variable speed and if the load is variable should also be gathered. Where it is possible, the data should also include information about flows. The list should include all of the equipment exceeding a certain level of energy or power consumed.

By reviewing the historical energy consumption and power demand by the WWTP as a whole as well as any components that are individually metered, an image of the electrical usage is acquired. If possible, performance tests on the most energy consuming equipment should be conducted to determine the power drawn and the efficiency.

Excessive use of energy, as a result of poorly implemented and poorly tuned control systems, can sometimes be a large cost bearer. Thus it is important to have an understanding of the current process control procedures applied at the WWTP. By defining the control strategies for the different processes, individually and as a whole, a necessary knowledge base is constructed which is vital for further investigations and optimization of the parameters controlling the process.

5.2 Analysis of collected data

When information about the current process has been collected, the information must be thoroughly analysed to maximize the possibility of implementing a proper energy saving plan.

An initial analysis should involve investigating the electrical agreement. As described earlier, the electrical usage cost generally consists of different fees, based on the energy usage and the power demand respectively. By calculating the amounts of these different fees, an understanding of the most effective electrical conservation methods may be obtained. The conclusions drawn from these calculations result in a number of recommendations or guidelines. These will be treated in the next subchapter.

The second part of the analysis should focus on the actual energy consumption or actual power demand of the different parts of the purifying equipment. This is the main part of the analysis and is also the most time consuming.

When analysing collected data, it is important to involve the process operators and maintenance personnel, who can offer experienced, practical and fresh feedback. They often constitute a great source of information and ideas, which can be achieved by arranging individual interviews or brainstorm group meetings.

Sometimes the measuring and logging of different energy-related parameters are poor. If lacking a wattmeter, the energy usage for equipment working at constant-speed can be estimated if a run-time logging is available. By achieving plate information of at which constant power level the equipment is working, the energy usage can be easily calculated. For variable-speed equipment, e.g. pumps and compressors, estimation is harder to achieve; without a wattmeter the actual mean power is unknown. There are methods, though, to estimating the actual electrical usage if at least some measuring equipment is available. Below, a description is found on how to indirectly calculate the power demand for the two largest energy consumers at a WWTP, i.e. the main pumps or any pump respectively the aeration compressors.

The power a pump requires is related to the volume of fluid it pumps as well as how high it has to pump this volume. The relation is presented in equation 5.1. (Water Environment Federation 1997)

$$P = \frac{9.81 \cdot Q \cdot h}{e_T} \tag{5.1}$$

where

P = motor input power for pump [kW]
Q = pump flow [m^3/s]
h = pump total dynamic head [m]
e_T = e_p*e_d*e_m; e_T is the overall operating efficiency of the pumping system, whereas e_p, e_d and e_m are operating efficiencies of the pump, drive and motor respectively, in decimal equivalents.

As an example, consider a variable pump delivering 0.5 m^3/s with a dynamic head of 15 m and with an initial overall efficiency of 0.65. According to power equation 5.1, this corresponds to a motor power input of 113 kW. After 10 years, the efficiency has presumably decreased to 0.6. With this new overall efficiency, the same flow and head requires a motor input power of 122 kW. Thus, the new motor power demand exceeds the initially required power input by more than 8%. If the pump is presumed to be operational 80% of the year, the annual energy difference is

$$(122 - 113) \cdot 3{,}600 \cdot 24 \cdot 365 \cdot 0.8 = 238\,GJ = 66\,MWh\,.$$

An assumed average electrical cost of 0.75 SEK/kWh results in an annual financial loss of approximately 50,000 SEK. This example involves many assumptions, but it gives a clue to the relatively large financial proportions. At most WWTPs, the massive influent flow requires larger and/or more pumps, making the financial losses even more noticeable.

It is easily understood that these methods for estimation of energy usage require unnecessary efforts and involve uncertainties, compared to having relevant measuring equipment installed. Hence it is strongly recommended to install essential measuring equipment, e.g. wattmeters, connected to energy consuming equipment of interest.

Another positive aspect of knowing the actual power or energy consumed by e.g. a pump is that equation 5.1 can be used for calculating the efficiency. Due to wear, this parameter naturally decreases with time. Feedback of even a small efficiency decrease is very important, especially considering the large power levels of a main pump or an aeration compressor at a WWTP.

Considering the other large power demanding equipment, i.e. the aeration compressors, the calculations are not as straightforward and exact as the ones performed for the main pumps. Additionally, the research concerning the aeration equations is not yet fully settled. One way of calculating the aeration power is to use the expression for the power necessary in one single aeration zone, as described by equation 5.2. (Jeppsson 2005)

$$P = 0.4032 \cdot \frac{V}{V_{ref}} \cdot K_L a^2 + 7.8408 \cdot \frac{V}{V_{ref}} \cdot K_L a \tag{5.2}$$

where

P = motor output power for compressor [kW]
V = volume of aeration zone [m^3]
V_{ref} = volume of reference aeration zone [m^3]
K_La = volumetric oxygen mass transfer coefficient.

However, equation 5.2 is based on a specific kind of aeration system and a reference volume of 1333 m^3. Hence, the use of equation 5.2 is limited, and knowledge of the specific aerators must be achieved before the relation can be used.

5.3 Creation of an energy management plan

The collection and analysis of essential data should be followed up by an interpretation of the data. This should lead to a list of recommendations, constituting the basis of the upcoming energy management plan.

Starting with the electricity agreement, the performed analysis of this should lead to a number of initial recommendations of the energy management plan. These recommendations do not directly involve suggestions of how to reduce the actual energy consumption. Instead, they focus on how to lower the energy costs by changing the operative times of the equipment and also show which measures are most essential; reducing the energy consumption or reducing the power demand.

For example, the obvious first action for a WWTP company, with a relatively high power demand charge, would be to focus on reducing this demand. This could be achieved by evening out the power consumption throughout the day. Another example is agreements involving different energy fees depending on which time of the day the energy usage occurs. This may make it profitable to, if possible, change the distribution of the operative time over the day for the WWTP purifying equipment, e.g. by moving processes with a high-energy consumption to the low cost night time. If not already implemented, another suggestion for reducing the power demand is to apply a variable control to one of the main pumps instead of the normal intermittent operation. The result of this would be a more balanced system. The variable pump would be used for small changes in the power demand instead of starting one of the intermittent pumps, constantly requiring its maximum power demand. The power reduction would equal the difference between the unoccupied intermittent pump's power demand and the momentary demand from the variable pump. Additionally, this would most likely result in advantages to the wastewater treatment process.

The recommendation list should continue with listed suggestions concerning how to reduce the energy consumptions. These suggestions can involve larger as well as smaller changes in design or operation of the WWTP. Consequences for each change recommendation should be thoroughly investigated, diminishing uncertainties as far as possible – especially for more expensive investments. Examples of consequences could be presumed impacts on the process quality, cost calculations, such as payback time, etc. Other WWTP companies could already have implemented some of the recommendations. Although the process environments are likely different, the implementation results in these WWTPs should be regarded and used as a great support when obtaining a view of the consequences of the different suggested recommendations.

Considering the pump example in chapter 5.2 again, one action would be to invest in a new pump. This measure would require an influent stop or flow redirection for the installation to be realizable. It would also involve calculating payback-time for the investment costs. Naturally, postponing the necessary date for the investment would be favourable. One important way of doing this is by applying continuous measures in form of preventive maintenance. This prolongs the operative lifetime of any mechanical equipment, such as pumps or any other, often expensive, equipment involved in the purifying process at a WWTP.

If not already implemented, a plan for preventive maintenance should be a part of the energy management plan. A maintenance plan should, at least, involve all of the essential energy equipment at the WWTP, instructions on how the maintenance should be performed for each part of the equipment and also within which time intervals the maintenance should be carried out, e.g. on a weekly, monthly or annually basis. To most of the relevant equipment, the responsible producer or seller delivers a basic maintenance manual, making the creation of a maintenance plan easier. Considering the specific process conditions at the specific WWTP, more or less modifications of the seller's maintenance suggestions are likely to be necessary.

5.4 Implementation of energy management plan

The single most important step when conducting an energy management project is of course the actual implementation of the plan. After thorough investigation of the consequences of the suggested plan, it is time to execute these suggestions of operation change and to perform the measures required. An implementation almost always leads to new knowledge, from which new questions and answers arise. Hence there is a close iterative connection between the different steps of a management plan.

The implementation of an energy management plan naturally varies significantly between different projects. Thus, different implementation measures are to be taken depending on the strategy of the current management plan. It is hence difficult to establish any common strategies when performing this part of the energy conservation project. Instead, an individual implementation plan should be set up in every unique project, constituting the basis for the subsequent work.

5.5 Evaluation

Naturally, any project should be concluded by an evaluation of what has been done, how it has been done and what this has resulted in. These evaluations should be gathered during a long time period to include influences of varying conditions throughout e.g. a year; different conditions can have different impact depending on where and how the recommendation has been implemented.

As mentioned earlier, the process of energy management is highly iterative. The evaluation of an implemented change could also be regarded as a form of data collection, hence initiating a new loop of the energy conservation process resulting in yet another energy management plan.

An example of the iterative correlation between the different steps in an energy management plan is brought up in a book presented by Danfoss Analytical (Ingildsen, Olsson 2001). It concerns a pre-denitrification plant, where it was stated that the denitrification was not fully utilized. In the pursuit of correcting the problem, a nitrate sensor was installed in the end of one of the denitrification reactors. This revealed a nitrate concentration mainly measuring 0 mg/l. A test was then performed to the specific reactor, where an increased nitrate recirculation rate was tested. This showed that the normally automatically controlled recirculation pump was already running close to its maximum capacity. Hence, the pump was set manually to constantly pump at maximum speed. The positive results could soon be easily distinguished with a noticeable improvement in the quality of the effluent water.

Naturally, it is preferable to achieve implementation results as qualitative as possible, leading to a more reliable evaluation. Only considering the purification process parts of an energy management plan, a more reliable evaluation could be achieved if certain conditions are fulfilled. The most important condition is that the treatment process is divided between two or more parallel and reasonably similar lines. This would give the opportunity to test a suggested implementation on one of the lines and then comparing it with a line not experimented with. With the two different line measurements occurring during the same period, conditions like load variations, wastewater constituents and temperature are almost identical. This leads to an evaluation based on more reliable information compared to if the two scenarios had been applied to the same line, but at different times. A good example of these benefits was shown in the Danfoss example presented above, where the effects of manually increasing respectively not increasing the recirculation could be simultaneously measured and compared.

6 Energy management applied at Himmerfjärden WWTP

In this chapter, the general methodology introduced in chapter 5 is applied to the specific situation at Himmerfjärden WWTP.

6.1 Energy and power agreement

As mentioned earlier, it is of great importance to understand the agreement made between the electrical service provider and the customer. By adapting the energy utilization to the agreement, cost-reducing potentials can be found instantly.

At Himmerfjärden, as at most WWTPs, the electrical fees consist of a fixed customer charge, an energy charge and a power demand charge, as mentioned in chapter 4.1. At present, these three different charges are divided between two companies. Vattenfall is the owner of the electricity supply network and thus, the company collecting the fixed customer charge and the power demand charge respectively. E.ON is the utility company responsible for delivering the required energy amounts, thus being the company profiting from the energy charge. The fixed fee applied to Himmerfjärden WWTP consists of a customer charge of 50,000 SEK/year and a measuring fee of 25,000 SEK/year.

The power demand fee is divided into two different fees depending on which time of the year the usage occurs. The base cost during all months is 86 SEK/kW. In addition to this, there is a supplementary cost during the five high cost months (November – March) of 162 SEK/kW. The current power demand level at Himmerfjärden is set to 4.0 MW. The total cost for the power demand can hence be calculated:

$$(86 + 162) \cdot 4{,}000 = 992{,}000 \, \text{SEK/year}$$

By comparing the total costs for different levels of the power demand, a clear picture of the money saving potential in power reduction can be achieved. As an example, a reduction of the power demand from the current level at 4.0 MW to 3.5 MW would result in a total cost reduction from 992,000 SEK/year to 868,000 SEK/year, i.e. 124,000 SEK/year.

However, the general trend for WWTPs is an increased power demand due to more complex treatment processes. This is the situation at Himmerfjärden WWTP as well and hence a power demand reduction here is unlikely, unless some sort of power-limiting application is implemented. One such solution is a power safeguard, which will be further discussed in chapter 6.3.

The penalty fees for exceeding the agreed power demand limit are often relatively high. At Himmerfjärden WWTP today, each kW above 4.0 kW results in a penalty charge corresponding to two times the low cost power demand fee. Additionally, during the high cost months, the penalty fee is increased by one and a half times the high cost power demand fee. As an example, during a period with heavy rainfall in the summer of 2005, Himmerfjärden WWTP exceeded the power demand level during a period of four hours with a maximum of 4.7 MW. The total penalty fee for this usage was 120,000 SEK.

Concerning the energy cost, no large distinction is made between high cost time and low cost time. At Himmerfjärden WWTP the energy fee is constant at 0.5174 SEK/kWh. The moderate difference is found in the transfer fee where the high cost fee is 0.019 SEK/kWh and the low cost fee is 0.014 SEK/kWh. This gives an approximate constant energy cost of 0.53 SEK/kWh. The total energy usage for Himmerfjärden WWTP for 2005 was approximately 23.43 GWh, resulting in a total electrical energy cost of 12.5 MSEK.

In addition to the usage at Himmerfjärden WWTP, some smaller processes along the way of the tunnel system require energy, e.g. pumping of wastewater. The total energy usage for these processes is approximately 2.34 GWh and the cost for this energy usage totals approximately 1.24 MSEK. However, this usage is not included in the energy conservation plan.

Since there is almost no time-related difference in the fee for energy use, no consideration has to be taken regarding methods trying to reduce the total cost by controlling the energy utilization to be situated at low cost time. The tool in reducing energy costs will instead be to use the current energy utilization processes in a more effective way, and to try to avoid excessive usage.

A complete list of the electricity rates can be seen in table 6-1. Furthermore, the relation between the fixed electricity costs, e.g. the customer fee and power demand fee, and the variable energy costs, is illustrated in figure 6-2.

Table 6-1 List of rates according to the current energy agreements.

Customer fee	50,000	SEK/year
Measuring fee	25,000	SEK/year
Power demand fee		
Low cost time	86	SEK/kW
High cost time	162	SEK/kW
Energy cost	0.53	SEK/kWh

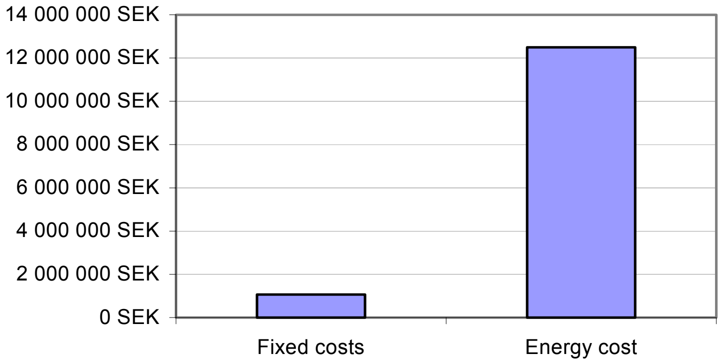

Figure 6-2 Distribution of the fixed costs, including customer fee, measuring fee and power demand fee, and the electrical energy costs at Himmerfjärden WWTP.

6.2 Consumers

In accordance to the methodology presented in the previous chapter, a list of the most energy or power demanding equipment is required. Due to inadequate energy usage logging at Himmerfjärden WWTP, the list is based on the most power demanding equipment. The largest power consumers of the list can be found in table 6-3. For a complete list, see appendix A.

Table 6-3 Table of the most power consuming equipment at Himmerfjärden WWTP.

Equipment	**Total power**
Main pumps	6,015 kW
Aerating compressors	1,000 kW
Pumps, fluidised bed	200 kW
Process water pump, sedimentation	180 kW
Centrifuges, sludge treatment	134 kW
Sludge recycling, aeration basin	132 kW
Tunnel fans	100 kW

Due to the delimitation concerning the project time, a selection of the equipment with the highest cost reduction potential has been made. Hence, some of the equipment in table 6-3 is not included in the energy management plan presented in this thesis.

6.2.1 Main pumps

The main pumps located at the inlet of the WWTP are accounted for a large part of the energy usage at Himmerfjärden. The inlet's location 54 meters below ground level causes a quite extreme situation where large volumes of water are elevated to ground level. To overcome the pressure difference, a total of 6,015 kW in pumping power is installed.

Since the influent water under all conditions must be elevated to ground level, no energy savings can be done in the process itself due to the laws of physics. Instead, the possible energy savings can be achieved by increasing the efficiency of the process. An investigation made by Vattenfall in June 1995 established that the pumping efficiency was good and that replacing the pumps would not result in an improved efficiency (Lundquist 1995). But since this investigation was performed more than ten years ago, it is strongly recommended that a new investigation concerning the main pump's efficiency should take place.

It is also of great importance that a maintenance program is implemented to make sure the pumping equipment is in the best possible condition. As a result of the large flows and the high elevation, even the slightest improvement in pumping efficiency would result in a rather large decrease in energy usage, and consequently reduced energy costs.

6.2.2 Aeration system

Second to the main pumps, the aeration is the most power demanding process at Himmerfjärden WWTP. The aeration at the WWTP is taken care of by four individually controllable 250 kW compressors, providing the aeration basins with air. The four compressors are all linked to the same aeration system, which is connected to all of the eight aeration basins. Individual control of the basins is taken care of by an adjustable valve located at the inlet of each basin's aerating system. By changing the valve's opening angle, it is possible to control the amount of air supplied by the compressors. Each basin can hence be individually controlled.

The average total aeration power at Himmerfjärden WWTP during 2005 was 650 kW. This gives an annual total energy usage of approximately 5.7 GWh and hence an energy cost of roughly 3 MSEK per year. Considering the large costs involved in the aeration process, it is important that attempts to optimise the process as far as possible are made.

At present, the control of the aeration is based on oxygen concentration levels measured by a sensor located 15 meters from the end in each one of the eight 96 metres long aeration basins, as shown in figure 6-4. The sensors are positioned 20 centimetres below surface. At this depth, the oxygen is considered to be fully absorbed.

This approach to the aeration control strategy is referred to as manual set point control. The WWTP operator decides an adequate level of oxygen concentration in the aeration basin. The power input to the aeration compressors is then adjusted to fulfil the oxygen demand in the basins.

By controlling in this manner, no consideration is taken to the relative differences in oxygen level inside the basin. Instead, only a measurement of the oxygen level at the location of the sensor is received. The need for differences in oxygen input in the different parts of the basin is instead taken care of by a change in density of the aerators. As shown in figure 6-4, each basin is divided into six zones, with a difference in density of the aerators, which was calculated when designing the WWTP. Hence there are no possibilities of controlling the oxygen input individually in the different zones.

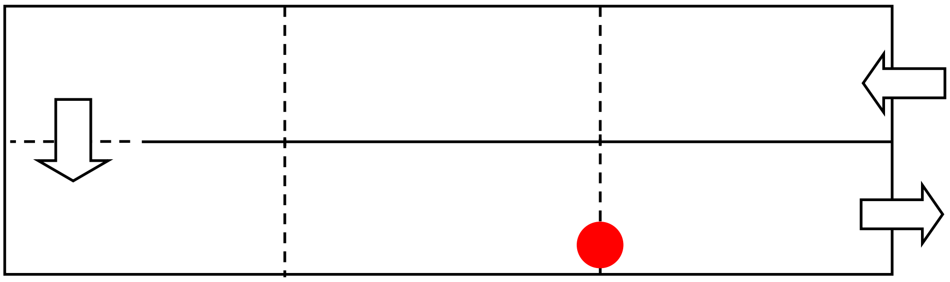

Figure 6-4 Layout of the aeration basin at Himmerfjärden WWTP. The dot indicates the position of the oxygen sensor.

Manual set point control offers the advantage that excessive aeration can be avoided to some extent. Furthermore, a constant oxygen concentration level offers consistent conditions for the bacteria. However, it is difficult to realise what level of oxygen concentration is needed. Excessive aeration caused by too high levels of oxygen is an expensive luxury. An evaluation of the current aeration strategy should hence be performed when trying to reduce the energy costs.

Since the aeration system is a complex process, optimizing the dissolved oxygen control is far from an easy task. Nevertheless, it is possible to achieve an understanding whether a change in control strategy is beneficial or not. As always, when discussing optimization of any process, one has to be aware of not only the possible economical profits gained by a change in strategy, but also the consequences in the process quality itself. This is also the case when trying to optimize the aeration process, where it is important to balance process cost against process quality.

A few approaches to optimize the aeration process exist. One approach is to simply comply with the effluent demands at the lowest possible cost. One other approach is to set a maximum level of aeration cost, and to get the best possible effluent quality for the money. One alternative way of formulating the balance, e.g. applied in Denmark, is to assign values to the effluent levels. For example, the cost of the total nitrogen in the effluent can be set at 100 SEK per kilogram. By doing this, it would be possible to calculate the total operating cost of the WWTP, including the process cost and the effluent quality. The optimizing goal would be to minimise this total cost. (Ingildsen, Olsson 2001)

The decision to what extent the effluent quality may be affected by minimising the treatment process cost should be discussed in every unique case. At Himmerfjärden WWTP, the total nitrogen in the effluent is set in accordance with governmental regulations at a maximum of 10 mg/l. No demand for the ammonium level is set, but at the effluent a maximum ammonium concentration of 2 mg/l of preferred. All values are based on an annual mean value.

Currently an oxygen concentration of 3.5 - 4 mg/l is set at Himmerfjärden WWTP. The rate can be considered to be high, but can be justified by the relatively short process time. At Himmerfjärden WWTP, the water passes the aeration basin in a total of approximately four hours. This can be compared to the average aeration process time at most WWTPs of approximately ten to twelve hours. Nevertheless, there is still a capacity for a change in the oxygen level and hence a potential for a more efficient aeration process.

As mentioned earlier, with the current control strategy there is no control of the relative difference of oxygen level in the six zones of the aeration basin. To receive a picture of how the oxygen differs between the different zones a measurement must be performed. By measuring the oxygen levels in the different zones and averaging the values, an oxygen profile is received. Measurements made in January 2006 give the profile shown in figure 6-5.

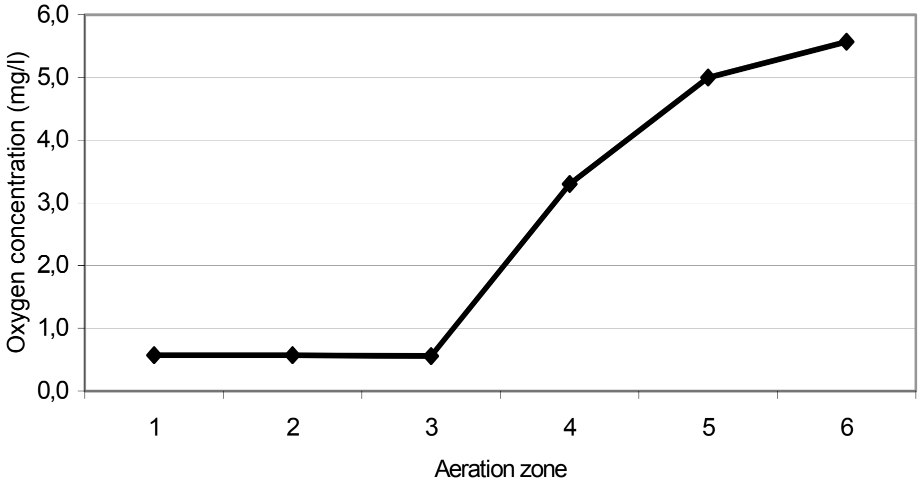

Figure 6-5 Oxygen concentration profile in the aeration basins based on measurements made in January 2006.

The oxygen profile indicates that there are distinct differences in measured oxygen concentration between the first three zones and the last three zones of the aeration basins. This can be explained by the design of the aeration basins. As shown in figure 6-4, the basins are shaped as a 'U', with a fall shaft in the turn between zone three and four, preventing the water in the second part to return to the first part. The constant level of oxygen in the first half and the rapid increase in the second half is a consequence of the fact that the basins are submitted to constant mixing. Turbulence in the basins, caused by the aerating process, levels out the oxygen concentrations in the two halves.

By studying the oxygen concentration profile above another conclusion can be made. When the oxygen measurements, on which the oxygen profile is based, were made, a set point of 3.5 mg/l was set. Now looking at the oxygen profile chart at zone five where the oxygen sensors are installed, an oxygen concentration of 5.0 mg/l is found. Given the complex nature of the process, this can of course be the result of many factors, but most likely because of poorly working oxygen sensors. The explanation can be confirmed by the fact that the sensors in this specific case actually did show a value of approximately 4.0 mg/l. Insufficient maintenance in form of calibration and cleaning of the sensors might be the reason for this. Hence it is of great importance that a proper maintenance program is applied to make sure the equipment is in good condition to avoid excessive aeration. Regular maintenance would secure a condition where process engineers can obtain a better view and better control abilities of the current process state.

Furthermore, the low oxygen level in the first part of the aeration basin can cause problems in the nitrification process. Constant low levels of oxygen can stimulate growth of a certain type of filamentous bacteria (Jenkins et al. 2003). The shape of these bacteria causes development of a bulking sludge, which may cause problems in the treatment process. Additionally, this problem may be further enhanced by the relatively low COD load to the plant. A low COD load results in a low F/M (food to micro-organisms) ratio, which in combination with low oxygen concentration have been reported as a possible cause for sludge bulking.

Considering the ammonium profile for the aeration basins presented in figure 6-6 below, based on measurements performed in March 2003, another explanation of the increase in oxygen concentration in the second half can be found. When reaching the last zone of the aeration basin, the ammonium concentration is low, and almost no nitrification occurs. Since low amounts of oxygen are consumed, the oxygen concentration increases rapidly.

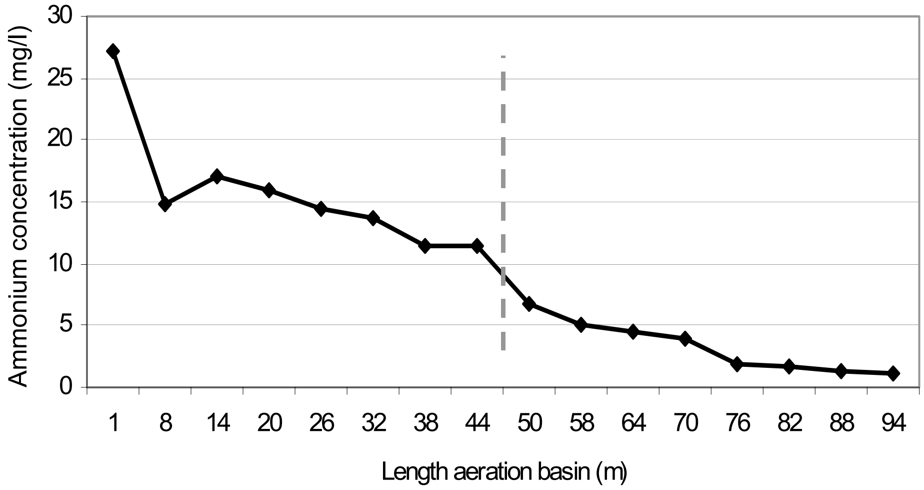

Figure 6-6 Ammonium concentration profile in the aeration basin based on measurements performed by SYVAB. The grey striped line represents the position of the fall shaft in the middle of the basin

The facts discussed above suggest a different strategy in controlling the aeration process. Due to the large differences in oxygen concentration between the two parts of the aeration basin, only small possibilities are given to the process engineer to actually control the nitrification and the oxygen distribution only by measuring at one location in the basin. A more flexible approach would be to install another oxygen sensor in the first part of the aeration basin. By controlling the different parts individually, an ability to control the oxygen levels for the two parts is given. This would not only result in better conditions for controlling the process, but also better abilities for a more efficient energy usage.

As discussed earlier, the aeration process is very complex and its result depends on many factors. Furthermore, the dynamic nature of a wastewater treatment process increases the complexity. Hence it is very difficult to verify in what way a change in control strategy will affect the process behaviour. A full-scale experiment is not only an expensive and time-consuming method, but can also cause a negative influence on the recipient in an extent that cannot be allowed.

An effective and rather inexpensive tool when evaluating a suggested strategy change is a computer model. Developing a computer model can also be considered being a quite difficult and time-consuming task, but once the model is working it is a useful tool. In this thesis, a model developed by a Task Group (Henze et al. 2000) for the International Water Association, IWA, has been used in the environment Matlab/Simulink. The name of the existing model is the Activated Sludge Model No. 1, ASM1.

The ASM1 is a biological model, including dynamic processes to describe growth and decay of biological material as well as nitrogen transformation. The biological model is further described in Henze et al. (2000). To model the settling processes a one-dimensional, ten-layer model, is used with a settling velocity function according to Takács et al. (1991).

The model has been modified and calibrated to fit the conditions at Himmerfjärden WWTP. Standard values for parameters suggested by the IWA have been used. The only exception is the value for the nitrification speed, where a reduced value is set. The following text in this subchapter will present and discuss the results when verifying different control strategies in the aeration process at Himmerfjärden WWTP running the computer model. A principal layout of the simulated model is shown in figure 6-7.

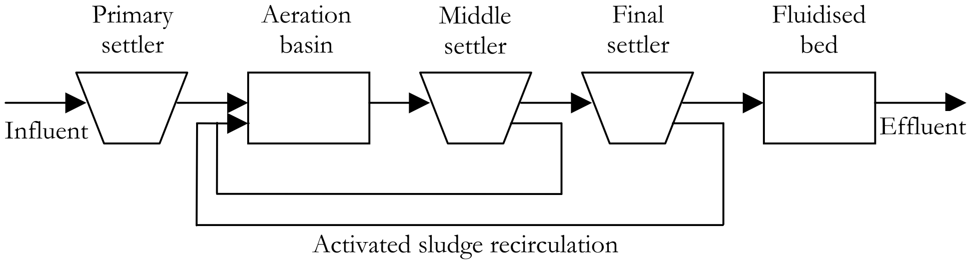

Figure 6-7 Principal layout of the simulation model.

By comparing the measurements of the oxygen concentrations and the ammonium concentrations in the aeration basins at Himmerfjärden WWTP with the results achieved when running simulations in Matlab/Simulink, the model behaviour can be evaluated. As shown in figure 6-8 and 6-9, the result of the simulations is similar to the real situation. A constant level of oxygen in the first half of the basin is followed by a linear increase. However, a limitation when using the model is the nitrification process behaviour. The model has some difficulties to simulate the actual nitrification process, and tends to exaggerate the process speed. But since the different simulations always are compared by the relative nitrification result, no consideration has to be taken to the absolute nitrification result.

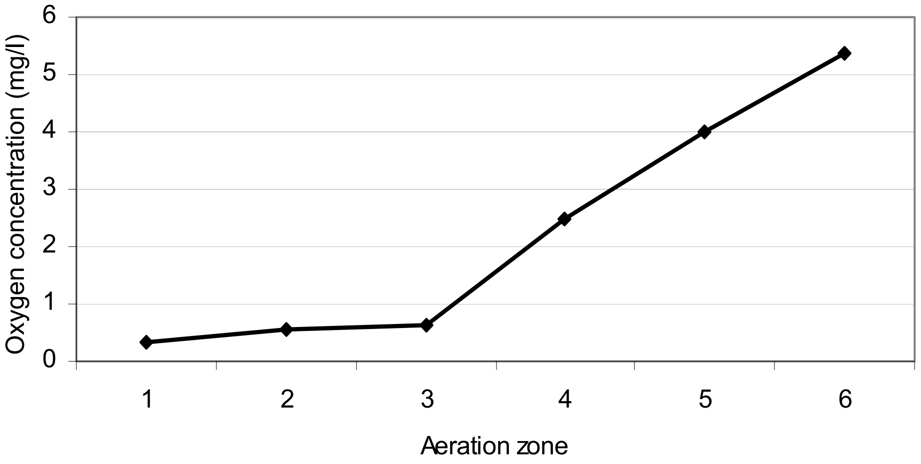

Figure 6-8 Oxygen concentration profile achieved by simulation in Matlab/Simulink.

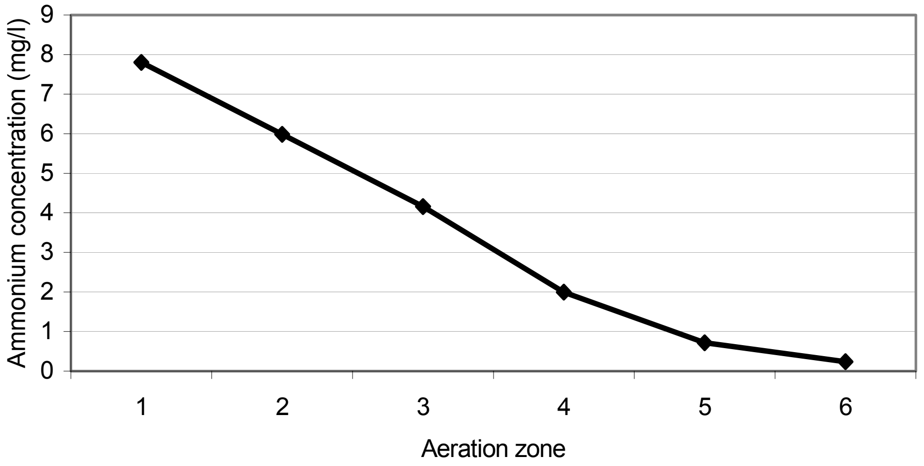

Figure 6-9 Ammonium concentration profile achieved by simulation in Matlab/Simulink.

Following the discussion presented earlier in the chapter, installing a second oxygen sensor in the first part of the aeration basins will improve the controllability and the process behaviour. Simulations in Matlab/Simulink verify this. By comparing this strategy with the control strategy applied today, a more even distribution of the oxygen concentration is achieved, and hence excessive aeration in the latter zones can be avoided. Results are displayed in figure 6-10 and 6-11.

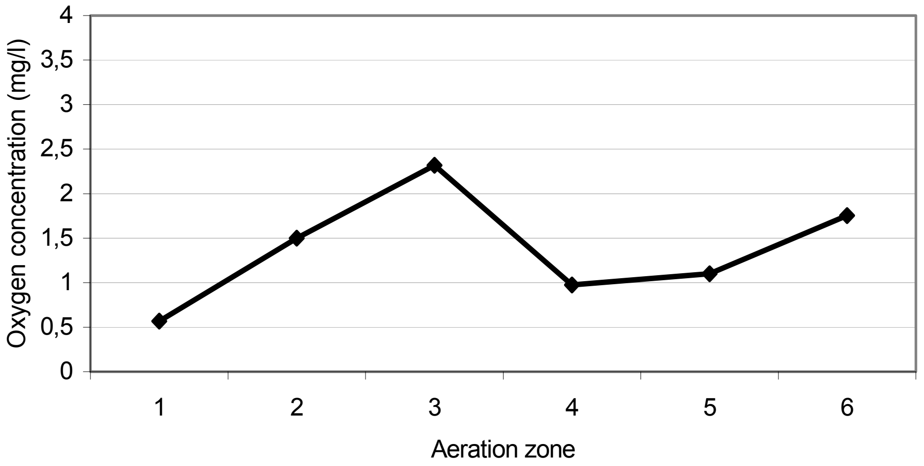

Figure 6-10 Oxygen concentration profile achieved by simulations in Matlab/Simulink when controlling with a second oxygen sensor.

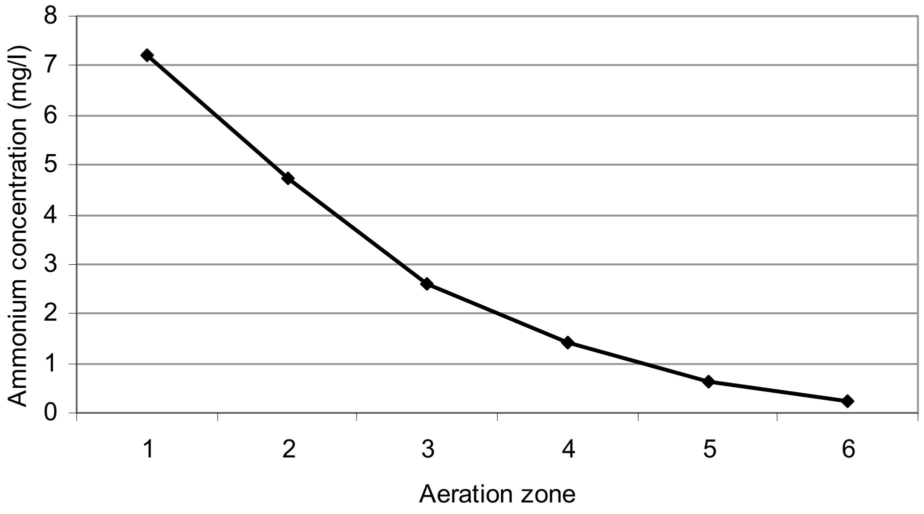

Figure 6-11 Ammonium concentration profile achieved by simulations in Matlab/Simulink when controlling with a second oxygen sensor.

Based on the same nitrification result, a control strategy with two oxygen sensors would result in an aeration energy reduction of 15%. With the current energy price applied at Himmerfjärden WWTP, an annual saving of 450,000 SEK would be achieved.

By installing an oxygen sensor at the end of the aeration basin, the possibility to control the oxygen concentration in the wastewater leaving the basin will increase. However, the measure has no or very limited effect on the process itself, and will not change the behaviour of the nitrification. Instead, positioning the sensors in the middle of the halves will give a better view of the oxygen level due to mixing conditions.

An additional way of reducing the aeration energy usage is to decrease the amount of supplied oxygen and consequently the level of nitrification, hence allowing an increased ammonium level in the effluent. This alternative would not necessarily imply an increased total nitrogen level in the effluent. Since the current regulations only concern the total nitrogen level in the effluent, the ammonium ratio in the effluent can be significantly increased without exceeding the governmental regulation. A discussion about the appropriateness of nearly complete ammonium removal should hence be initiated.

Another way to control the aeration process could be achieved by installing an ammonium sensor at the effluent of each aeration basin. This would make it possible to base the aeration control directly on the ammonium concentration of the wastewater leaving the basin. This approach is referred to as dynamic set point control. However, the specific situation at Himmerfjärden WWTP involves a relatively steady influent ammonium load in the aeration basins, resulting in a low-fluctuating nitrification process. Hence, under the present conditions, no significant increase in process quality or efficiency is achieved by implementing an ammonium control strategy. Instead, only a more direct way to control the ammonium concentration at the effluent is achieved. These conclusions are verified by applying the strategy to the computer simulation model, where no significant increase in process quality or efficiency is achieved by implementing dynamic set point control. Considering the large investment costs involved, an implementation of this strategy cannot be justified under present conditions.

6.2.3 Fluidised bed

The fluidised bed consists of four basins, each connected to a pump delivering 50 kW at maximum flow. The pump objective is not only to deliver water to the fluidised bed, but also to keep the sand, onto which the microorganisms are attached, suspended via the upward stream of water. Hence, a minimum flow is required at all time to establish the suspension of sand particles and consequently the denitrification. The minimum flow required is 1,500 m^3/h to each of the basins, resulting in a total flow of 6,000 m^3/h and a total power demand of 200 kW. Since the flow to the WWTP at most times is below the required flow to the fluidised bed, a recirculation of the wastewater is necessary. Already denitrified water is led back to the fluidised beds using the pumps.

By closing down one of the four basins, excessive energy usage due to the over capacity in the fluidised bed can to some extent be avoided. Usage of only three basins would result in a required flow of 4,500 m^3/h and a pumping power of 150 kW. On request by the authors of this thesis, calculations were made by personnel at Himmerfjärden WWTP concerning the operation of the fluidised bed. Based on data for the latter half of 2005, these calculations show that the total amount of nitrogen in the effluent water adds up to an average of 4.3 mg/l. A shutdown of one basin would result in an average total nitrogen increase in the effluent by 4.4 mg/l. This results in a total nitrogen amount of 8.7 mg/l. As mentioned earlier, a maximum level is set at 10 mg/l. However, a security margin for process disturbances has been specifically established at

Himmerfjärden WWTP. According to this, a maximum total nitrogen level of 8.0 mg/l in the effluent water is accepted.

A shutdown of one basin during a ten-month period would result in an average total nitrogen level of 8.0 mg/l, which is acceptable. However, due to differences in flow, nitrogen concentrations, sludge quality and process disturbances etc., further margins should be considered. Furthermore, a start up time of the closed basin should also be considered. A shutdown during eight months would hence be more realistic. This would lead to an annual energy saving of approximately 292 MWh. With the current energy fee the result would be an annual saving of approximately 155,000 SEK.

However, closing down one of the basins would result in a decrease in capacity of the fluidised bed. Nevertheless, this should be a minor problem since most of the time the flow does not exceed 4,500 m^3/h. Furthermore, the calculations above are based on values for a normal period. A change in process quality or influent concentration could result in different nitrogen levels, and hence a difference in effluent water quality. Hence, a shutdown time less than eight months may also be considered.

In addition to the reduction in electrical energy usage, the reduced denitrification results in a decreased need for added external organic source. At Himmerfjärden WWTP, methanol is added to the denitrification process to provide the microorganisms with the necessary organic substance. Data from the latter half of 2005 shows a methanol usage corresponding to approximately 3.0 kg methanol per kg reduced nitrate. If a linear decrease in the need for an organic source is assumed, a reduction in denitrification resulting in an increased nitrate level at the effluent from the current level at 4.3 mg/l to 8.0 mg/l, at a flow rate of 100,000 m^3/day would result in a decrease in methanol usage corresponding to approximately 1,110 kg per day. With a current methanol price of 2.80 SEK per kg, this would lead to an annual cost reduction corresponding to 1.1 MSEK.

Consequently, the large cost related to the usage of an external organic source should give rise to a discussion about the appropriateness and necessity of a denitrification quality exceeding the stated governmental demands. At least, it would be beneficial to gain an awareness of the cost of the organic source at the denitrification, and the potential of a cost reduction. As an example, at a wastewater flow rate of 100,000 m^3/day and a methanol price of 2.80 SEK/kg, the cost of the organic source required to denitrify nitrogen corresponding to a reduction of 1 mg/l is approximately 300,000 SEK per year. By allowing an increase in total nitrogen at the effluent, a rather large cost reduction would hence be achieved.

6.2.4 Tunnel fans

The purpose of the tunnel fans is to establish and maintain a pressure in the tunnel, which is lower than the atmospheric pressure at ground level. This difference in pressure is important to make sure no air from the tunnel leaks to the surroundings to avoid bad smell in residential areas.

The total power of the operating fans in the tunnel is 100 kW. Currently, the fans are constantly operating, thus giving an energy usage totalling at approximately 880 MWh/year. This gives a total annual energy cost for the fans of about 460,000 SEK. The rather high cost and operating strategy enables a potential to implement a more energy efficient control strategy with money savings as a result.

A way to avoid excessive usage of the tunnel fans would be to implement a control strategy where pressure meters are installed at ground level and inside the tunnel to control the usage of the fans. By operating the fans in an intermittent manner, activated only when needed, excessive energy usage by the tunnel fans could be avoided. An alternative method is to install frequency regulators on one or on both fans to reduce the fan speed when possible.

As an example, a 20% fan power reduction will result in a decrease in energy usage with 176 MWh/year, i.e. 92,000 SEK/year.

6.3 Load management

After implementing the suggested Himmerfjärden-specific recommendations, the power demand should be noticeably lower, together with a possible reduced energy consumption. This would give an opportunity to lower the electrical costs related to the power demand. Additionally, data from year 2004 and 2005 show that the actual total maximum power demand very seldom exceeded 3.5 MW, also favouring a reduced power demand. However, a reduced power demand would involve smaller safe margins and thus greater risks of exceeding the settled power limit. Hence, it would be favourable to implement some kind of safeguard into the electrical system. This safeguard would limit the power demand to the agreed higher limit in case of an exceeded power requirement from the treatment process.

The suggested solution with a safeguard system is also known as priority load shedding or load management, i.e. the scheduling and control of electric equipment to eliminate the risks of exceeding a certain total power limit. The control handling can be achieved either manually or automatically, but the general trend is toward automatically controlled systems. One option is that the scheduling and control is integrated into the existing overall computer control system used at Himmerfjärden WWTP. A second option involves investing in an external package solution, offered by different manufacturers. Both options presume knowledge of the total momentary power required at the Himmerfjärden WWTP. The easiest, most accurate and most inexpensive way to achieve this information is to make an agreement with the utility company, which at present could be either Vattenfall or E.ON. The metering system of one of these companies could be connected with the Himmerfjärden WWTP control system and used as an input of the necessary total momentary power consumption.

Whichever option chosen, the idea of priority load shedding is definitely a part of the Himmerfjärden WWTP future. Especially considering the relatively small negative effects it has on the purification process of a well-planed power shedding applied to, for example, the aeration process. This thesis has involved extensive modelling and simulations mainly of the aeration process. Among other aeration simulations, some has involved power shedding, which is further discussed later in this chapter.

While giving direct financial savings through reduced power demand and possibly a reduced energy consumption, the power safeguard suggestion also have negative consequences. The most evident one is the effect on the process quality, which often – though not always – is negatively related to financial savings. For example, if the aeration process requires a certain amount of energy, bringing the total power demand over the agreed limit, the safeguard would stop a part of the necessary aeration. This would lead to a less effective nitrification, resulting in a poor nitrate-purification and thus a higher amount of total nitrogen in the effluent. A suspected negative effect of the increased amounts of total nitrogen could be that the allowed annual limit, in accordance with Swedish regulations, of 10 mg/l is exceeded. Considering the present low effluent levels at Himmerfjärden WWTP, though, this would require a considerable amount of hours during which the safeguard is actively throttling the aeration energy usage.

If some of the suggested recommendations were implemented, the effluent situation would still not be noticeably different; the influence of even a considerable time of maximum total nitrogen release is relatively small when looking at an annual mean value. A way of showing this is to apply possible scenarios on the computer model.

Before presenting these scenarios and results, it should be clarified that a model never perfectly imitates the reality. Especially, when considering a process as complex as the purification at a WWTP. Though extensive calibrations have been made to the model, it has been necessary to set some delimitations when optimizing the model. The calibrations have been concentrated on getting approximately the same relative variations of the output values in the model compared with the data given from the real scenario, when changing input conditions. Hence, the aim with the calibrations has been to modify the model so that it reacts to input variations in the same way as the real process does, rather than trying to obtain model output values identical to the real output variables. Several different scenarios from the real process, e.g. with different influent flows depending on time of day or year, have been considered and constituted the base of the model calibrations. Naturally, this procedure leads to results, expressed in relative differences instead of actual figures. These relative differences could then be applied to the original values measured in the real process to achieve final results adapted to the real process.

One simulation scenario involves a four hour long total throttle of the aerators, resulting in an increase of the effluent total nitrogen level by 1% on an annual basis. As explained above, the focus is set only on these relative changes. In the same way, four hours of total aeration throttle occurring in all twelve months increases the effluent level of total nitrogen by 13%. In another example, applied to the computer model, the aeration is completely throttled for an entire day. This increases the annual mean total nitrogen outlet by almost 25%. To be able to discuss when the increase of the effluent total nitrogen levels becomes significant, the low effluent levels at present should be considered and compared with the allowed levels according to Swedish regulations. The last two years' annual mean value of approximately 5 mg/l of total nitrogen in the effluent could theoretically be increased by almost 100% and still be below the agreed limit of 10 mg/l.

The examples above treat a total throttle, which in reality would be extremely abnormal. Naturally, the extent of throttling depends on the agreed power demand limit. However, with a well thought-out limit the scenario would instead involve only a tiny throttle, occurring intermittently and summing up to only a few hours per month. This diminutive throttling would cause only a small fraction of the full throttle scenario and would hence, on an annual basis, result in almost no negative effects on the aeration process and effluent quality.

If the suggested priority power shedding is implemented at Himmerfjärden WWTP, the directly following recommendation is to reduce the power demand. As exemplified in chapter 6.1, a power demand of 3.5 MW instead of today's 4.0 MW would result in financial savings corresponding to 124,000 SEK/year. Additionally, according to the simulation scenarios presented above, such a power demand reduction would not cause any significant increase of total nitrogen in the effluent.

The power demand at Himmerfjärden WWTP exceeded 3.5 MW only 28 hours during the period January till October in 2005 and only a few more hours in 2004. Considering this data and the discussions presented above, it can be concluded that priority load shedding together with a reduced power demand to 3.5 MW is highly feasible already today. Of course, the costs related to such an investment is vital. The exact costs vary depending on the complexity of the system as well as the manufacturer, but a qualified and realistic assumption is a payback time of approximately two years, possibly even less than that. This payback time results in a strong recommendation of investing in a priority load shedding system.

When considering a power priority list of the different process parts it is natural to investigate the most power requiring equipment, because these involve the greatest potential of power reduction. If only considering the load management, the obvious first part of the process to investigate would be the main pumps. In earlier discussions, e.g. presented in chapter 6.2.1, it is motivated why the focus has been set on the aeration process and why the main pumps have been less prioritized. That is why the main part of this subchapter has been centred on the aeration process.

An interesting peak power reduction alternative, involving the main pumps, exists though. Hypothetically, one or more of the main pumps could be stopped, if the safeguard system has registered a total power consumption, risking to exceed the agreed power demand. Due to the temporarily higher inlet flow, compared to the flow pumped up to the ground floor, one disadvantage with this solution would be that it would require the end of the inlet tunnel respectively the screening room to allow an increased wastewater level. Buffering the incoming wastewater here could lead to negative effects later on in the treatment process, e.g. with too much digestion activity occurring. The inlet buffer alternative has not been investigated in this report, but another master thesis is being conducted concerning this matter. When finished and available, the thesis should be thoroughly studied (Masengo N. 2006).

6.4 Energy contributors

The two most potent energy contributors at Himmerfjärden WWTP derive from the digester gas production respectively the heat energy conserved in the treated effluent water. Today, the energy produced in these two processes is far from fully utilized and is mostly lost as heat energy into the atmosphere or the ocean.

6.4.1 Digester gases

During summer, approximately 4,200 m^3 of digester gas is combusted each day in the so-called "torch", and is released into the atmosphere. From September to October year 2005 this amount corresponded to approximately 44% of the total gas production in the bioreactors. With an energy content of 24 MJ/m^3, the equivalent energy loss for September 2005 was 840,000 kWh (Wahlman, Sjögren 1987).

The utilized parts of the digester gases are used for heating the sludge dehydrating process as well as heating the WWTP facilities, e.g. personnel facilities and offices. The sludge dehydrating process requires temperatures of approximately 360°C and hence, a lot of heat energy.

In wintertime, the gas production in the bioreactors is only enough for providing the dehydration with heating energy. The heating energy required to maintain the right temperature in the WWTP facilities must be extracted from somewhere else than from the burning of digester gases. Today, this heat comes from oil, which is combusted in two combined gas and oil central heating boilers. These two boilers are suspected to have low efficiencies and should be exchanged, upgraded or at least analysed in a near future. A third heating boiler also exists; a newly installed boiler in which only digester gas can be used for heating.

If the produced digester gas could be entirely or partly used for purposes other than providing the sludge dehydration process with heat, one important alternative would be to extract electric energy from the gases. This would be achieved by installing a gas power engine. However, further investigation and calculations concerning the gas power engine alternative are outside the scope of this master thesis. It is strongly recommended, though, to proceed with the gas engine related ideas brought forward in this thesis. An investigation concerning this matter has been done and is included in a report, presented by the consulting firm Theorells Energikonstulter AB in 1987 (Wahlman, Sjögren 1987). This investigation was done in 1986 though, which clearly indicates the necessity for a new investigation. Nevertheless, a summary of an example from the Theorells report can be presented to illustrate the potential of this possible electric energy source.

In the Theorells report it is stated that with a total available gas power of 2 MW, an engine efficiency of 30% and an operative time of 80%, a 600 kW gas power engine could be installed and generate electricity corresponding to 4,200 MWh/year. According to the present energy agreement this would equal an annual saving of 2.2 MSEK, which should be put in relation with the investment and installation costs, resulting in a payback time. As mentioned earlier, the gas production and thus the amount of excessive gas varies considerably depending on the time of year, i.e. the outdoor temperature and influent temperature etc. Additionally, at present, part of the produced digester gas is combusted and used for the sludge dehydration. Hence, this gas power engine suggestion involves many uncertainties and should be thoroughly investigated before a possible investment is realised.

In spite of that the thermal efficiency for a gas power engine is not much better today than when the example above was investigated 20 years ago, other differences clearly speaks for a new investigation. The 70% of the gas engine energy not generated as electricity, is transformed to heat energy. The technique to extract this heat energy has been developed since the year of 1986. It would be highly interesting to further investigate the possibility and potential of extracting heat from the gas power engine. The optimal scenario would be to combust all of the produced digester in a gas engine and that, except for the wanted electrical energy achieved, the additionally produced heat energy would be sufficient to supply the required heat to the sludge treatment and dehydration. Most likely, though, not enough heat energy could be extracted from the gas engine, but it could cover most of the required heat with the existing supplementary oil boiler producing the rest.

Another option of how to make use of the digester gases is to treat it and sell it as bio fuel, as mentioned in chapter 4.3.1. As explained, the digester gases must be partly purified to be allowed as biogas, according to Swedish regulations. This possibility has not been further investigated in this thesis. It has been stated that investing in a digester gas purification system is an expensive and complex task, but a more thorough analysis should be performed concerning this alternative.

6.4.2 Heat energy in the effluent and treatment process

The other large unutilized energy source is the heat energy conserved in the Himmerfjärden WWTP effluent. During the cold parts of the year when heating is especially needed, the average temperature in the effluent water is approximately 13°C. A realistic suggestion is to extract heat energy so that the effluent temperature is lowered to 4°C, which is the natural temperature at the ocean floor, where the effluent is released.

According to an example presented in the Theorells report, the energy lost through the effluent at Himmerfjärden WWTP amounted to approximately 0.65 TWh for the year of 1986. This investigation was based on the temperature difference presented above. The mean influent flow during the test period was 116,000 m^3. With some of this influent exiting the system through e.g. removed sludge, but also with an addition of liquid through the methanol in the fluidised bed, it can be assumed that the influent approximately equals the effluent. During the last years, the effluent has fluctuated around 100,000 m^3 per day, depending on which part of the year it is. Using the linear correlation between effluent flow and heat energy loss from the year of 1986, the present annual heat energy loss can be interpolated, equalling approximately 0.56 TWh.

With these facts presented, it is obvious that the massive amounts of lost heat energy should be extracted and recycled in some way. One way of attending to this matter is to invest in a heat pump system. A high quality heat pump of today has a coefficient of performance of approximately 4.0. This coefficient stands for the ratio between the heat energy output and the necessary electrical energy input, i.e. 1 kW of electricity input delivers 4 kW of heat energy. Theoretically, the difference between the heat energy output and electrical input equals the heat energy input by the heat source, which in this case would be the effluent water.

With the basics of the heat pump explained, another way of calculating the lost effluent energy can be presented to verify the very sparsely accounted calculations of the Theorells report. The relevant energy relation is presented in equation 6.1.

$$W = c_p \cdot m \cdot (T_2 - T_1) \tag{6.1}$$

where

W = heat energy [J]
c_p = specific heat capacity [J/(kg*K)]
m = mass [kg]
T_2-T_1 = temperature difference

As mentioned earlier, the effluent in 1986 averaged 116,000 m^3 per day, corresponding to an annual total water volume of 42.3 million m^3. Assuming that 1 m^3 of purified water weighs 997 kg results in an annual total water mass of 42.2 billion kg. By extracting heat from the effluent, the average temperature is lowered from 13°C to 4°C, giving a temperature difference of 9°C or 9 K. Under the given conditions with atmospheric pressure and normal temperatures, the c_p, i.e. the energy needed for heating 1 kg of a specific substance 1 K, for the water is assumed to be the commonly used value of 4,180 J/(kg*K). With this data, according to equation 6.1, the total amount of heat energy possible to extract is 1,588 TJ or 0.441 TWh. In the Theorells example, the suggested heat pump's coefficient of performance was assumed to be 3.0, resulting in a total heat energy output from the heat pump of 0.66 TWh, which is approximately the same answer as in the report. Applying the same calculation procedure on the corresponding data of today, but with the coefficient of performance set to 4.0, results in a present possible heat energy production of 0.51 TWh. If a coefficient of 3.0 is used instead, the result is a heat energy output of 0.57 TWh, thus almost equalling the answer from the linear interpolation used earlier.

As seen in the calculations above a heat pump with a higher coefficient of performance results in a lower energy output than one with a lower coefficient. Intuitively it may be expected that a higher heat coefficient should result in a higher energy output. Studying the relationship presented above, though, it is understood that the profit with a higher coefficient is that a lower amount of electricity is needed for the constant heat energy source. Because the output theoretically is the sum of the electrical and heat energy sources, a lower supply of electricity energy naturally leads to a lower energy output.

To get a clue of the relatively vast heat energy potential in the effluent, further information can be extracted from the Theorells report. Among other things, it is estimated that the necessary energy for heating the Himmerfjärden WWTP's process buildings, administrative areas, underground areas and sludge digestion tanks totalled almost 9,000 MWh in 1986, i.e. corresponding to 1.6% of the effluent heat energy potential.

Because of the enormous heat energy potential, the optimal solution for recycling the heat energy produced at Himmerfjärden WWTP would be to connect the suggested heat pump system to a district heating system. As with most WWTPs though, Himmerfjärden WWTP is situated far from any district heating plant as well as from any larger domestic areas; the nearest district heating plant is situated in Södertälje, at a distance of 23 km. Unfortunately, the geographical situation hence makes this idea financially untenable.

Though the geographical position of the WWTP is unfavourable, an effluent heat energy extraction would have its advantages. It would give heat energy enough to totally or partly free the possible excessive gas amounts for other purposes. One important alternative has already been discussed in chapter 6.4.1.

Another part of the treatment process, where a possible heat extraction is evident is the intermediate sludge storage, where digested sludge is storied before the sludge treatment process. When entering the temporary storage, the digested sludge has a temperature of approximately 37°C. The top of the storage silo is totally open to the atmosphere, resulting in a large and unnecessary heat loss. Though needed later in the sludge treatment process, most of the sludge heat is lost when transported and centrifuged. Hence, a possible heat extraction here would not lead to any particular negative effects. To analyse the heat energy extraction potential, data of the flow rate into the silo has to be collected. There has not been enough time for collecting reliable data of the specific flows in this thesis, which results in a recommendation for further investigation concerning this possible solution.

7 Conclusions

In this chapter, the results when applying the energy management plan at Himmerfjärden WWTP will be presented and discussed in a brief manner. Recommendations and consequences for implementing the recommended measures will also be discussed. Furthermore, a recommendation of future works will be given.

7.1 Summary of results

The most evident result achieved when conducting the energy conservation project was the efficiency of the current operation of the aeration in the biological treatment process. By rather simple measures, a control strategy involving two oxygen sensors in each basin instead of one could be implemented. Running computer simulations in Matlab/Simulink showed an energy usage reduction of 15% by controlling in this manner. With today's energy price, this corresponds to an annual cost reduction of 450,000 SEK. In addition to a more efficient energy usage, more suitable conditions for the microorganisms would be achieved due to a more even oxygen distribution, resulting in an increased sludge quality. The discussion about the aeration system can be found in chapter 6.2.2.

The analysis of the fluidised beds indicated a potential in operative change resulting in a more energy efficient process. Since there is a rather large overcapacity in the operation of the fluidised beds, a shutdown of one of the four beds would be possible. Calculations showed that a shutdown during eight months per year would be possible, without exceeding the demands stated regarding the annual average total nitrogen effluent. This would result in an annual energy usage reduction of approximately 292 MWh, i.e. 155,000 SEK with the current energy price. Furthermore, the action would result in a decreased need for an organic source corresponding to 1,110 kg/day. The annual saving due to this would correspond to 1.1 MSEK/year. For a complete discussion concerning the fluidised beds, see chapter 6.2.3.

Further potentials concerning energy conservation could be achieved by implementing some sort of control strategy in the tunnel fan operation. Since the electrical equipment, handling the ventilation of the tunnel, is rather power demanding, even a small decrease in power consumption would result in a noticeable decrease in energy usage. According to an example presented in chapter 6.2.4, a 20% average reduction in fan power would result in an annual energy usage decrease of 176 MWh, resulting in a reduced energy cost corresponding to 92,000 SEK/year.

According to the discussion in chapter 6.3, a reduction of the power demand may be possible, resulting in a decreased power demand cost. Usage of a power demand safeguard would secure the power demand being kept below the limit. A suggested new power demand limit when using a power safeguard is 3.5 MW, resulting in a lowered power demand cost of 124,000 SEK/year. However, the cost reduction should be put in relation with the possible negative process consequences and the investment costs involved.

7.2 Recommendations

Since the main pumps are accounted for such a large part of the energy utilization, an efficiency survey of the pumping equipment should be performed. If the efficiency is considered to be low, an investment in new equipment can be favourable, despite of the high investment costs. Furthermore, it is essential that the pumping equipment is included in a maintenance program, making sure the pumps are in a condition allowing them to work at the highest efficiency possible.

Concerning the aeration system, a change in control strategy would definitely be beneficial. The control strategy presented in this thesis would not only offer the advantage of being more energy efficient, but also offer better and more consistent conditions for the process itself. Hence, a change in aeration strategy is recommended.

Furthermore, a thorough investigation concerning the operation of the fluidised beds should be performed to study the possibilities to implement the strategy presented in this thesis. During this work, a discussion concerning the value of keeping the nitrogen effluent values far below the governmental demand stated should be brought up.

As mentioned, a potential for a power demand reduction, resulting in a cost reduction, does exist. However, this option should be investigated further before an actual implementation can be considered. Costs related to a possible power demand safeguard system investment should be put in relation to the cost reduction achieved, hence resulting in a pay back time.

Development and implementation of a maintenance plan would secure a situation where the processes involved in the treatment operation are working in an adequate manner. Regular maintenance of electrical motors, pumps, sensors and other equipment is essential for making sure no excessive energy usage occurs due to wear or poor calibration. Hence, development of a maintenance plan is recommended.

7.3 Future works

Future works should include an investigation of the potentials of extracting energy from the different processes in the treatment operation. Electric generation by combustion of digester gases could be an option leading to a system of renewable energy. Another option is to implement a system allowing sale of biogases to external buyers, thus letting the biogas production acting like a source of income. This option should hence be investigated further.

Extraction of heat energy at the effluent and in the sludge treatment should be considered as yet another option for energy extraction.

Further investigations of the priority load shedding option should be undertaken. The effect a throttle of the main pumps would have on the tunnel system should be investigated before taking further actions concerning an implementation of a power demand reduction.

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Appendix A – Power Consumers

Consumer	Location	Power [kW]	Quantity	Total power [kW]
Main pumps	Main pump station	2*520+475+3*1500		6015
Aerators	Pump station 2	250	4	1000
Water pump	Fluidised bed	55	4	220
Process water pump	Pump station 3	45	4	180
Centrifuges	Sludge treatment	15+18,5	4	134
Return sludge pump	Pump station 2	22	6	132
Tunnel ventilation	Gärtuna, Hågelby	45+55	1	100
Dispersion pump	Flotation	18,5	5	92,5
Sludge pump	Pump station 2	15	4	60
Compressor	Tunnel	55	1	55
Circulation pump	Digestion chamber	15	3	45
Compressor	Tunnel	45	1	45
Effluent pump	Flotation	15	3	45
Feed water pump	Flotation	15	3	45
Drying rotor	Sludge treatment	45	1	45
SP 6, 7, 8	Pump station F	15	3	45
Sludge pump	Pump station 1	22	2	44
Feed water pump	Effluent	37	1	37
Sludge pump	Pump station 3	15	2	30
Circulation fan	Sludge dewatering	30	1	30
SP 10	Pump station F	30	1	30
Ventilation	Flotation	26	1	26
Fan room, supply air	Tunnel	7,5	3	22,5
SP 1-2	Pump station F	11	2	22
Ventilation	Flotation	20	1	20
SP 5	Pump station F	18,5	1	18,5
Sludge pump	Pump station 1	15	1	15
Sludge pump	Pump station 1	15	1	15
Agitator	Sludge storage	15	1	15
SP 4	Pump station F	15	1	15
Sand pump	Pump station 1	4,7	3	14,1
Effluent pump	Flotation	13,5	1	13,5
Fan room, exhaust	Tunnel	11	1	11
Effluent pump	Flotation	11	1	11
Sludge pump	Sludge storage	11	1	11
SP 3	Pump station F	7,5	1	7,5