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Energy Analysis within Industrial Hydraulics and Correspondent Solar PV System Design

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# DEGREE PROJECT

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Abstract

Energy efficiency and renewable energy use are two main priorities leading to industrial sustainability nowadays according to European Steel Technology Platform (ESTP). Modernization efforts can be done by industries to improve energy consumptions of the production lines.

These days, steel making industrial applications are energy and emission intensive. It was estimated that over the past years, energy consumption and corresponding CO$_2$ generation has increased steadily reaching approximately 338.15 parts per million in August 2010 [1]. These kinds of facts and statistics have introduced a lot of room for improvement in energy efficiency for industrial applications through modernization and use of renewable energy sources such as solar Photovoltaic Systems (PV).

The purpose of this thesis work is to make a preliminary design and simulation of the solar photovoltaic system which would attempt to cover the energy demand of the initial part of the pickling line hydraulic system at the SSAB steel plant. For this purpose, the energy consumptions of this hydraulic system would be studied and evaluated and a general analysis of the hydraulic and control components performance would be done which would yield a proper set of guidelines contributing towards future energy savings.

The results of the energy efficiency analysis showed that the initial part of the pickling line hydraulic system worked with a low efficiency of 3.3%. Results of general analysis showed that hydraulic accumulators of 650 liter size should be used by the initial part pickling line system in combination with a one pump delivery of 100 l/min. Based on this, one PV system can deliver energy to an AC motor-pump set covering 17.6% of total energy and another PV system can supply a DC hydraulic pump substituting 26.7% of the demand. The first system used 290 m$^2$ area of the roof and was sized as 40 kW$_p$, the second used 109 m$^2$ and was sized as 15.2 kW$_p$.

It was concluded that the reason for the low efficiency was the oversized design of the system. Incremental modernization efforts could help to improve the hydraulic system energy efficiency and make the design of the solar photovoltaic system realistically possible. Two types of PV systems where analyzed in the thesis work. A method was found calculating the load simulation sequence based on the energy efficiency studies to help in the PV system simulations. Hydraulic accumulators integrated into the pickling line worked as energy storage when being charged by the PV system as well.
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1. Introduction

1.1 Energy efficiency and CO$_2$ emissions in the steel industry

Nowadays steel making industrial applications are energy and emission intensive. It was estimated that over the past years, energy consumption and corresponding CO$_2$ generation has increased steadily reaching approximately 338.15 parts per million in August 2010 as shown in figure 1.1 [1].

![Figure 1.1 Statistics of atmospheric CO$_2$ level [1]](image)

Two distinguished ways of industrial emission production were identified: the energy related way and the manufacturing process related way. This classification is shown in figure 1.2. Energy sources of emissions can be divided further into direct and indirect groups. In case of direct emission production, the residuals are spreading after the fossil fuel burning process, and indirect source refers to the electricity consumption by different manufacturing systems [2].

![Figure 1.2 Classification of industrial sources of emissions](image)

The steel production process involves several manufacturing steps when task-oriented systems are connected together with product and by-product interactions [3]. The energy efficiency indicator,
Specific Energy Consumption (SEC), is used as a measure of used energy by an industrial process in relation to useful output by the same process as it is shown in equation 1.

\[
SEC = \frac{E_{USED}}{P_{PRODUCED}} = \frac{E_{ELECTRICITY} + E_{OTHER}}{P_{PRODUCED}} \tag{1}
\]

Where, \(E_{USED}\) is the energy which was used to produce particular amount of the product, \(P_{PRODUCED}\) in tones. This energy can be divided into two main components \(E_{ELECTRICITY}\) and \(E_{OTHER}\). The first indicates the electrical energy use and the second other types of the energy sources involved into the production chains.

In a similar way, the specific CO\(_2\) emission intensity indicator shows the relation between total amount of the emissions by the product produced which is shown in equation 2 [4].

\[
SpecificCO_2 = \frac{CO_2Emissions}{P_{PRODUCED}} \tag{2}
\]

Energy Efficiency Index (EEI) is used to monitor SEC and can be calculated as in equation 3 where the reference values of SEC are used.

\[
EEI = \frac{SEC_{REF}}{SEC} \tag{3}
\]

The energy efficiency indicators are used as the policy making measures and can be applied for international comparisons as well.

The overall energy research brings to the surface some questions regarding effective energy use by steel industries. Industrial lines are the tight composition of many components performing necessary tasks chiefly consisting of hydraulic systems driven by motors. Any changes towards effective energy use by industrial systems can catalyze the growth within steel manufacturing. Even slightly decreased energy demand would impact total steel production cost in a positive way thus improving its profitability and competitiveness. It would also affect sustainability polices by reducing environmental effects from the industry.

System innovations in energy intensive industries such as steel production are of great importance. “Industrial transformation” towards effective energy use is one of the important subjects nowadays. Design of technologies must be optimized in a manner where they can meet better energy standards [5].

Lately, two fundamental issues leading to industrial sustainability were identified by the European Steel Technology Platform (ESTP). These are energy efficiency and renewable energy use. This period in time is seen by them as an intermediate period for adapting the changes and doing the modernization efforts [6].

### 1.2 Environmental visions of the SSAB Group

The SSAB Group is amongst one of the world’s biggest companies and has a specialization in the field of metallurgy. It conducts part of the high-strength steel production processes in Borlänge,
Sweden. This part includes hot and cold rolling mills, coating and after-treatment lines. The product range includes strip in thicknesses ranging from 0.1 mm to 16 mm, with a maximum width of 1,600 mm. The products are marketed under the Domex, Docol and Prelaq brands. Hot-rolled advanced high-strength steel is used, among other things, in the automotive industry primarily for trucks, and in areas such as cranes and containers. Cold-rolled advanced high-strength steel is mainly used for safety components in the automotive industry [7].

A high level of attention is given to the environmental questions by the SSAB Group and it is one of the world’s leaders in terms of limiting emissions from production. One of the main visions of the SSAB Group is “a stronger, lighter and more sustainable world” when high strength steel can be produced in the environmentally friendly way. SSAB aims to make contributions to a globally sustainable future by reducing carbon dioxide (CO₂) emissions in conjunction with steel production. It is supporting the EU project, ULCOS, for steel manufactures which has a goal of reducing today’s CO₂ emissions by at least 50 percent. SSAB also wants to reduce CO₂ emissions by at least 2% per ton of steel in today’s steel production.

In Borlänge the SSAB group is aiming to reduce energy consumptions per tone of the steel by 10% at the end of 2011 compared with 2006.

Further research into possibilities of replacing a certain amount of its electricity requirements by its production through renewable sources of energy is a part of the SSAB vision.

### 1.3 Solar energy generation and utilization

Solar energy has been under utilized since the existence of man. The sun’s rays have included two important types of energy, namely light and heat and this has been known for some time. The real question has been how to utilize and harness these forms of energy to humans’ benefit [8].

Solar energy comes from the sun which is composed of mostly hydrogen and helium gases. At the core of the sun, hydrogen atoms fuse together to make helium and thus release energy during this process known as nuclear fusion. This is the energy that reaches the earth every day.

When hydrogen atoms fuse together to form helium, a certain amount of matter is lost during this process and is emitted into space as radiant energy. It is interesting to note that although it takes millions of years for the energy in the sun’s core to reach the surface of the sun, it only takes it about eight minutes from the solar surface to reach the earth while it travels at the speed of light.

It is also an amazing fact of nature that just a tiny portion of the sun’s radiant energy reaches the earth (one part in two billion) and even this amount is huge. To give an example, the energy that hits the USA in one day is enough to supply the country’s needs for one and a half years if captured and utilized properly [9].

It also needs to be understood how a lot of the sun’s energy gets used up. For instance, about 15% of this energy is reflected back into space while 30% of it evaporates the water thus producing rain clouds and eventual rainfall. Oceans, land, and plants of all kinds also absorb a lot of this energy. What is left is more than enough to be used by humans to satisfy everyone’s energy requirements on the planet [9].
In a solar cell which is also known as a photovoltaic or PV cell, the sun’s energy is directly converted into electricity. When multiple number of cells are connected in an electrical manner and put into a frame, it is called a PV module or solar panel and when a group of PV panels are combined, these are called arrays [10].

Silicon is usually used as the material of choice to manufacture photovoltaic cells due to its semiconductor properties. These semiconducting properties are enhanced when silicon is doped with impurities such as phosphorus to make n-type silicon or with boron to make p-type silicon. When light (photons) hits a solar cell, the semiconductor material absorbs a part of its energy enabling it to knock off some of the electrons loose which results in their free flow. When an electric field in the solar cell forces the electrons to flow in a certain direction, it eventually results in an electrical current [9].

Figure 1.3 shows a PV cell and how the electrons are knocked off.

![Figure 1.3 PV cell and its make-up](image)

1.4 Objectives of the thesis work

The scope of the thesis work is to make a preliminary design and simulation of the solar PV system which would attempt to cover the energy demand of the initial part pickling line hydraulic system at the SSAB steel plant. For this purpose, the energy consumptions of this hydraulic system would be studied. The research would be based on the measurements and corresponding calculations of the energy input into the system and energy output by it. The results can lead to an estimation regarding effective energy use within the studied hydraulic system and therefore a corresponding energy efficiency profile can be created. The general analysis of the hydraulic and control components performance can yield a proper set of guidelines contributing towards future energy savings.
The project tasks:

- Conduct energy analysis of the initial part pickling line hydraulic system in the SSAB steel plant.

- Do a general analysis of the hydraulic and control components performance which would yield a proper set of guidelines contributing towards future energy savings.

- Design and simulate the correspondent solar photovoltaic system which would make an attempt to cover the energy demand of the initial part pickling line hydraulic system at the SSAB steel plant.
2. Photovoltaic applications and their demand within industrial sector

2.1 Photovoltaic technology overview

The use of PV generated electricity is the same as electricity produced from conventional sources. PV systems can potentially supply electricity to any specific appliances or the electricity grid.

PV energy production is remarkable because it can adjoin to any other energy source traditional or renewable. It is extremely flexible in terms of its implementation because a PV system can be integrated into consumers’ nets or can be easily installed as a separate solution. The PV systems’ classification is shown in figure 2.1. Another unique property of the PV systems is that PV arrays can be built ranging from a few mille watts up to multi-megawatts.

![Figure 2.1 PV systems classification](image)

As can be seen from figure 2.1 there are two types of PV systems. The first is a grid connected system where the installed PV system is connected to the national electricity grid. This arrangement allows the owners to buy electricity from the supplier when the PV system does not fulfil needs and also to sell electricity to the supplier when extra electricity is produced by the PV system. The second type of system is an off grid or stand alone type of PV system. In this case, the system cannot be connected to the grid and batteries have to be used to store the generated electricity so that it would be used only when needed [11].

Nowadays photovoltaics is a well-established, proven technology with a substantial international industrial network. The industry of photovoltaics is growing fast and currently, photovoltaic products are available throughout the world. Installed PV systems are powering everything from individual devices to entire objects [12].

One example of the PV water pumping system is a 240-watt installation for powering a water pump which has the capability to distribute 270 gallons of water per hour through a drip irrigation system. The system was implemented in eastern Oregon, USA. It was stated that the use of silicon panels to convert sunlight to electricity have benefits beyond their contribution to reducing fossil fuel use and being cost-effective [13]. A solar water pumping system can look as depicted in figure 2.2.
One of the features of the photovoltaic pumping system which is useful for the present work is that the system runs the hydraulic pump directly. This is because along with the development of PV systems which produce energy in DC form, there is the corresponding development of DC motors technology and therefore DC brushless hydraulic pumps are finding their way into the market now.

Another example of photovoltaic technology which can be helpful in this thesis work is a type of PV system which delivers power to an AC load. Lightening, refrigeration and ventilation PV based systems can be a good example when their electrical circuit is powered from photovoltaic energy generation. The typical PV system for these kinds of facilities would encompass a PV modules array, an inverter, AC connections boxes, and circuit breakers as shown in figure 2.3.

PV installations can also generate power for big consumers such as different kind of industries as well as simple generation of power in order to supply to the public grids. The diagram in figure 2.4 gives an overview of the overall PV development in the Europe [15].
The large and medium scale applications in 2010 are taking 12% of the total PV development distribution. The biggest sectors belong to PV solar home systems and PV grid-connected systems of small scale. Sustainable growth of the European Photovoltaic Industry reflects the PV installations growth in the period of time from 1994 to 2010.

The International Energy Agency (IEA) imposes a classification of the grid-connected photovoltaic systems in relation to their size and is developing certification guidelines in the European market. PV systems can be separated as:

Small = 10 kW or less with single-phase output
Medium = 10 kW to 100 kW with three-phase output
Large = 100 kW with three-phase output that may employ internal protection and required utility relay protection

PV installations must be safe and satisfy the proposed IEA technical requirements. The certification tests which are developed nowadays can help to check the working abilities of the photovoltaic systems but cannot evaluate the performance parameters of PV installations [16].
3. Hydraulics and energy use in the steel industry

3.1 Principles of hydraulics and industrial hydraulic systems

In the classification of hydraulic systems there are two main groups. Figure 3.1 below shows this separation into mobile or movable to the spot and fixed non-movable machines. Industrial or stationary applications are non-movable oil hydraulic systems of fixed machines which can be placed in a specific manufacturing environment. These systems are based on fluid power when an incompressible fluid solution transforms and does work through a set of pipes towards the hydraulic motors and pumps. Industrial hydraulic systems can cut, press, lift and do several other innumerable actions within the manufacturing processes [17].

![Hydraulic systems classification](image)

Figure 3.1 Hydraulic systems classification

The working principle of any hydraulic system is based on the conversion of small forces into bigger forces employing hydraulic fluid. Figure 3.2 below shows a simple hydraulic press which consists of two pistons and a pipe connecting them. When pressure is applied from one side, it is transferred to another load side with a system multiplication factor. According to Pascal’s law, the working fluid spreads the pressure with the same force into different areas [17].

![Hydraulic press](image)

Figure 3.2 Hydraulic press

Energy conversion into hydraulic form can be considered a very effective way of energy transfer. This is because it is possible to move heavy things and implement different working options with higher precision and flexibility. Reliability of the hydraulic system can be achieved through the use
of pressure release components. But the most important factor is the ability to exercise precise control over the hydraulic system and make it predictable and repeatable.

The mechanical energy of the prime mover, figure 3.3 below, is transferred into hydraulic energy, and the two parameters of torque and shaft speed are converted into pressure and flow by the hydraulic pump. The hydraulic motor, which is next in the chain on figure 3.3 converts pressure and flow back into mechanical energy. When mechanical energy is converted into hydraulic form, it can be easily transferred into different locations because the pressurized fluid can flow freely through pathways reaching remote locations without significant energy losses.

3.3 Pickling line hydraulic system of the SSAB steel plant

The pickling line of the SSAB steel plant is the industrial system line which is integrated into the overall production process as shown in figure 3.4. It is placed after the hot rolling and finishing mills where the metal thickness is reducing by rolling when the material is exposed to the elevated temperature of 860 °C. In the finishing mill the temperature of the material is reduced to 650 °C.
The oxide film is formed on the steel surface due to chemical reactions of the heated metal surface with the oxygen in the atmosphere and is called scale. The scale covers the entire surface of the metal and must be removed from it by a process which is called pickling. The pickling process may have two steps when mechanical actions such as flexing and stretching are used to crack the surface and afterwards, when the material enters the acid bath where the scale is removed by means of chemical reactions [19].

The SSAB steel plant has two different types of pickling lines. One line is the continuous pickling line and another is the push-pull pickling line. The lines are industrial systems with many components and complicated interconnections between them. They have a few hydraulic and mechanical systems which work almost independently from each other.

The pickling lines can either work automatically or work under manual supervision. For the push-pull pickling line, manual supervision is used when the metal coil is entering the line. The metal coil must be lifted and installed into the working position. Only after the mechanical manipulations, can the metal be sent into the acid bath, be rinsed and then collected back into the coil, figure 3.5.
Figure 3.5 Schematic diagram of the Pickling Line

The hydraulic system of the push-pull pickling line has two parts. The first part of the line is initial, which is doing manipulations with the metal sheet before the acid bath and the second part is the finishing part which works afterwards. The initial part of the pickling line hydraulic system is used to set the metal coil into the starting position and to cut the inappropriate fragments of the metal sheet with the wrong thickness. The two parts of the push-pull pickling line are fully separated. There are different electrical connections and control for each one of them.

The initial part of the push-pull pickling line would be studied in this thesis work. Its structural block diagram is shown in figure 3.6. This part of the pickling line is a finished industrial high pressure open loop hydraulic system. The pressure in the main line of the hydraulic system must be between 140-160 bar.

Figure 3.6 Block diagram of the initial part pickling line hydraulic system

As can be seen from figure 3.6, five powerful electrical motors are running continuously throughout the whole year to run the variable displacement hydraulic pumps. These pumps deliver
energy into the high pressure hydraulic line. Furthermore, mineral oil is used in the line as hydraulic media. The main components of the hydraulic system are:

- The Hydraulic Oil Tank
- The Cooling system
- The electrical motors and pumps
- The hydraulics units

The hydraulic oil tank contains the hydraulic media. It has a filter system to remove particles and water from the oil.

The cooling system is used to maintain proper temperature of the hydraulic media because any hydraulic oil has limitation factors and can be easily destroyed under the influence of elevated temperatures.

The electrical motors are used to operate hydraulic pumps which are continuously delivering energy into the hydraulic system.

The hydraulic units are hydraulic actuators which perform different tasks in the line by converting hydraulic energy into mechanical power to do the operations. The hydraulic actuators are of two types: hydraulic cylinders and hydraulic motors.

One push-pull pickling line cycle is the time which is needed to process one metal coil. It includes a few distinguished steps:

- To place the metal coil into initial position
- To start the uncoiling of the sheet of metal
- To cut inappropriate parts of the metal sheet
- To cut the edges or to prepare for the acid bath
- To push the metal sheet through the acid bath
- To dry the metal sheet
- To collect the metal sheet back into the coil.

The average total time which the push-pull pickling line spends to process one metal coil is 20 minutes. The assumption of 20 minutes duration is used to describe one pickling line cycle in this thesis work. This time essentially depends on the thickness and weight of the metal coil.
4. Method of the Energy analysis: experiment design and energy efficiency calculations

The chosen method to do the energy efficiency calculations of the initial part pickling line hydraulic system is based on the pressure measurements for each hydraulic component integrated into the hydraulic system and the current measurements of the electrical motors which are delivering energy into the hydraulic system.

The pressure measurements and the current measurements were done simultaneously for a single pickling line cycle. Total duration of the pickling line cycle is twenty minutes.

The amount of energy consumed by and delivered to the hydraulic system by electrical motors is the data that is used to do the calculations for the overall system efficiency.

4.1 Experiment design

Pressure measurements in the initial part pickling line hydraulic system were done by using special measurement equipment of the ABB Group and recorded into the special software Argus Viewer. Each hydraulic cylinder and motor of the initial part pickling line hydraulic system has pressure sensors integrated into their hydraulic system to measure pressure from both ends as shown in figure 4.1.

![Pressure transducers diagram](image)

*Figure 4.1 Pressure transducers*

The experiment was designed in a way that the pressure was measured for 27 different hydraulic units, each one of which has its own hydraulic circuit, which are then connected to the common line of the initial part pickling line hydraulic system.

All pressure measurements were carried out simultaneously with the current measurements of the five electrical motors. The current measurements were also done by the measurement equipment of the ABB Group and recorded by special software Argus Viewer. The measurements in Argus Viewer are structured and stored into the separate files. They can be easily converted into the Microsoft Windows Excel form.
Figure 4.2 Argus Viewer software of the ABB Group

All further calculations and processing in the thesis work were done in the Matlab software.

4.1 Hydraulic actuators

The hydraulic energy which is generated by a hydraulic pump is transformed back into mechanical energy which can implement the tasks determined by the hydraulic actuators. Hydraulic actuators are separated into two big groups: linear or hydraulic cylinders (also known as jacks) and rotary or hydraulic motors.

4.1.1 Hydraulic cylinders

A hydraulic cylinder is a device which transforms hydraulic working energy into mechanical energy which is applied in linear direction to move a load. In hydraulics, the load is an object possessing a certain resistance. Physically, the hydraulic cylinder consists of a cylinder body, a closure at each end, a piston and a rod as it is shown in figure 4.3. The hydraulic cylinder has an inlet and outlet where the hydraulic media is entering and leaving the cylinder body depending on the movement direction. Through the cylinder stroke, the working hydraulic energy is applied to the area from the rod or piston side of the cylinder.
To size up the hydraulic cylinder, it is important to know the mechanical forces required to do the work. The force in hydraulics is directly proportional to the pressure and indirectly to the cylinder area. The next parameter which can characterize the hydraulic cylinder performance is the stroke or the distance which the hydraulic cylinder can travel. The cylinder stroke and area are determining the cylinder volume. It means that different cylinders can have the same volume but extract completely different forces.

The force of the hydraulic cylinder, $F_{\text{CYL}}$, is proportional to the pressure difference applied to the working area from the corresponding cylinder sides. It is measured in [N] and can be calculated from equation 4.

$$F_{\text{CYL}} = (P_1 \cdot A_1 - P_2 \cdot A_2) \eta_{\text{hm}} \cdot 100000 \quad (4)$$

Where $P_1$ is the pressure in [bar] from the piston side, $P_2$ is the pressure in bar from the rod side, $A_1$ is the area of the piston in [$m^2$], $A_2$ is the area from the rod side in [$m^2$] and $\eta_{\text{hm}}$ is the volumetric efficiency of the hydraulic cylinder.

Area $A_1$ from the rod and $A_2$ from the piston sides of the hydraulic cylinder can be calculated:

$$A_1 = \frac{\pi}{4 \cdot 100} D^2 \quad (5)$$

$$A_2 = \frac{\pi}{4 \cdot 100} (D^2 - d^2) \quad (6)$$

Where $D$ is the diameter of the cylinders' piston, and $d$ is the diameter of the cylinders' rod.

By knowing the force of the cylinder and its speed the power calculations, $P_{\text{CYL}}$, can be carried out because the cylinder power is directly proportional to the force and speed which can be seen from equation 7.

The power of the hydraulic cylinder is in [W] and the equation is:
\[ P_{\text{Cyl}} = F_{\text{Cyl}} \times s \]  \hspace{1cm} \text{(7)}

Where, \( s \) is the speed of the hydraulic cylinder in [m/sec].

The energy \( E_{\text{Cyl}} \) in [Wh] which is required to run the hydraulic cylinder is directly proportional to the cylinder power and can be calculated from equation 8.

\[ E_{\text{Cyl}} = P_{\text{Cyl}} \times \frac{\Delta t}{3600} \]  \hspace{1cm} \text{(8)}

### 4.1.1 Hydraulic motors

The hydraulic motor is a mechanical device which transforms the hydraulic working energy into rotary mechanical energy. This energy is further applied to a load or resisting object through the motor’s shaft because the motor consists of the rotating group attached to the shaft and inlet – outlet orifices.

![Figure 4.4 Hydraulic motor](image)

**Figure 4.4 Hydraulic motor**

As can be seen from figure 4.4, the rotating group is positioned off-center to the housing. The shaft is connected to the load and when the hydraulic fluid enters the inlet port, the force is becoming unbalanced and starts to turn the rotor. Before the motor’s operations, the vanes must be extended and positive seals must exist between vanes and housing.

The performance of the hydraulic motor can be estimated by establishing the motor torque. Torque \( T \) is a rotary or turning effort and is used as a force indicator and measures in Nm which is shown in equation 9.

\[ T = D_s \times \frac{Ap}{20\pi} \times \eta_{\text{hm}} \]  \hspace{1cm} \text{(9)}
Where $D_s$ is a motor’s displacement in [cm], $\Delta p$ is the pressure difference between the motors ports and $\eta_{hm}$ is the hydraulic motor volumetric efficiency.

Hydraulic motor power consumptions, $P_{MOT}$, is directly proportional to the motor torque $T$ and its angular velocity $\omega$.

$$P_{MOT} = T \times \omega$$  \hspace{1cm} (10)

Where $T$ is the motor torque and $\omega$ is angular speed in [radian/sec].

The hydraulic motor energy, $E_{MOT}$, is proportional to the motor torque and can be calculated in [Wh], as in equation 11.

$$E_{MOT} = P_{MOT} \times \frac{\Delta t}{3600}$$  \hspace{1cm} (11)

### 4.2 Hydraulic energy control

The energy transmitted in the hydraulic systems must always be under control otherwise no useful work can be done by the systems. The control in the hydraulic systems can be achieved by using different types of valves. The valves can mechanically connect or disconnect different passages or lines which are belonging to the hydraulic system. The hydraulic lines are carrying hydraulic media and the valves can control system pressure, flow directions and the flow rate within the lines.

When the hydraulic actuators are doing useful work, energy is being consumed in the hydraulic system but when the work is completed, the hydraulic pump continues to absorb energy from its prime mover and apply a higher pressure to the hydraulic media. Due to this situation, rising pressure would try to overcome the resistance which is created in the hydraulic line due to the physical strength of the system. In this case, pressure control valves must be used otherwise the energy entropy would tend to destroy the hydraulic system.

The pressure control valves have an internal moving part which is operated by pressure and when the pressure reaches a certain level, the internal moving part would let the hydraulic media move into a different direction and in this scenario, it is usually back to the system reservoir. A pressure control valve is shown in figure 4.5.
Hydraulic actuators, cylinders and motors can move in both directions. There are special valves which are capable of controlling the directions of the hydraulic media. The moving parts in the directional control valve connect and disconnect internal passages within the valve body thus allowing fluid movement in different directions.

The flow rate adjustments in the hydraulic system are done by flow control valves. By changing the flow rate in the hydraulic system, several different moving speeds of hydraulic actuators can be realized. Mechanically, the flow control valve is a resistance which results in a higher pressure being applied to the hydraulic pump. As a result, the pressure which is delivered to the actuator can be adjusted.
The flow control valve consists of the valve body, inlet and outlet ports, and tapered nose as shown in figure 4.7.

4.3 Hydraulic units data processing and evaluation

4.3.1 Press roll driving motor

Press roll driving motor is providing movements to the wheel which is part of the initial metal coil pre-process positioning system. The motor displacement is 60 cm$^3$, and it is assumed that rotational speed remains the same throughout its working time, which is 925 in [revolution/min]. This is an orbital motor which can move in both rotational directions or reversible motor. Figure 4.8 shows the photo of the motor position within the system on the left side, and its hydraulic circuit on the right side.
The hydraulic circuit of the press roll driving motor connected to the main loop of the pickling line hydraulic system line through the directional on-off valve (1). Two flow adjustment valves (2) are integrated between on-off and controlled proportional valve (3). Proportional valve is used to deliver hydraulic power to the motor depending on the directions of its expected rotations because the proportional valve determines pressure in the line. Pressure measurements for this motor were done at two points (6.1) and (6.2), as shown in figure 4.9.

![Figure 4.9 Pressure measurements of press roll driving hydraulic motor](image1)

After detailed analysis of the motor pressure measurements, it was established that the motor was used once during the pickling line cycle which was for twenty minutes in total duration. The motor worked continuously for 59.65 sec starting from 83.65 sec of the pickling line cycle up to 143.3 sec. The enlarged fragment of the pressure measurements which reflects the pressure gradient across the motor can be seen in figure 4.10.

![Figure 4.10 Working interval of press roll driving hydraulic motor](image2)

The press roll driving motor torque was calculated based on equation (9), which states that the torque of the motor is proportional to the pressure difference and the motor displacement, figure 4.11. The torque reflects the dynamic performance of the motor. As can be seen, it took some time
for the motor to reach its steady state level when the torque became constant and the motor started to work at its rated efficiency.

![Figure 4.11 Torque of press roll driving hydraulic motor.](image)

As can be seen from figure 4.11, the torque of the motor rose rapidly overshooting steady state conditions during the first 40 sec, after that followed intervals, when the motor torque had fluctuations overshooting and undershooting steady state borders. Overall, after 110 second the motor started to work with constant torque of 32 Nm, altered by ripples due to the nonlinear dynamic properties of the hydraulic circuit.

The power of the press roll driving motor was calculated using equation (10) and it is shown in figure 4.12. The power of the motor is directly proportional to the motor torque and angular velocity. In steady state conditions, the operating power of the motor was about 3kW.

![Figure 4.12 Power of press roll driving hydraulic motor](image)

The energy which was consumed by the motor during 59.65 sec was 0.05358 kWh, figure 4.13. This energy was the product of power and the corresponding time interval summed over the whole working range of the hydraulic motor.
4.3.2 Press Roll Hydraulic Cylinder

Within extension press roll cylinder moves the table of the metal coil pre-process positioning system, connected to the cylinders rod side, up towards the coil, and remains in that position until the coil would become adjusted to the working shaft, figure 4.14. The cylinder stroke depends on the metal coil diameter. The maximum possible cylinder stroke is 1200 mm, the bore diameter is 160mm, and the rod diameter is 110mm. The effective working area from the rod side is 0.0106 m$^2$, and from the piston side is 0.0201 m$^2$.

Figure 4.14 Image of press roll hydraulic cylinder and its hydraulic circuit
The press roll cylinder can be classified as a double-acting cylinder, as there are ports from both sides of the cylinder: from the cap end and from the rod end. Figure 4.14 on the right side contains its hydraulic circuit. Proportional valve (3) is used to adjust both flow and directions of the hydraulic media and the pressure reduced valve (4) adjusts pressure from the rod side because this pressure must be slightly less than from the cap side due to the smaller area to do work.

The pressure measurements were done across the cylinder at the points (6.3) and (6.4), which can be seen in figure 4.15.

![Press Roll Cylinder pressure vs time](image1)

Figure 4.15 Pressure measurements of press roll hydraulic cylinder

During the pickling line cycle, the press roll cylinder was used two times. The first time was from 76.15 up to 83.8 sec, when the cylinder was extracted, the second time was from 144 to 149 sec, when the cylinder was retracted, figure 4.16. The cylinder velocity was assumed constant at 0.16 m/sec because the data for the volumetric flow rate was not available for calculations.

![Press Roll Cylinder pressure vs time](image2)

![Press Roll Cylinder pressure vs time](image3)

Figure 4.16 Working intervals of press roll hydraulic cylinder
Figure 4.17 Pressure gradient across press roll hydraulic cylinder

The developing pressure difference when the cylinder was working is different for the two cases shown in figure 4.17. It can be seen that the first time, the difference was about 10 bar, whereas the second time it was about 70 bar. The big span in the values tells that the cylinder did not have similar load and presumably did not move with the same speed, which also reflects on the force graphs, figure 4.18.

Figure 4.18: Force and corresponding power of press roll hydraulic cylinder

The assumptions were made about the speed of the cylinder and about the length of its stroke. Constant speed of 0.16m/sec and the full length of 1.2m were used for the calculations. Cylinder power is directly proportional to the developed force and to the speed.
Figure 4.19 Energy consumptions of press roll hydraulic cylinder

Totally press roll hydraulic cylinder consumed 0.002902 and 0.0007139 kWh of energy.

4.3.3 Outboard bearing cylinder

The outboard bearing cylinder by configuration belongs to the double-acting type because it can carry load in both directions. The cylinder has two ports on both ends where the pressure can be built up. The effective pressure area is 0.0123 m$^2$ from the bore side and 0.0059 m$^2$ from the rod side. The stroking length of the cylinder is 1.170 m and the bore and the rod diameters are 0.125 m and 0.90 m respectively. The maximum speed which the cylinder can develop is 0.17 m/sec.

Figure 4.20 Image of outboard bearing hydraulic cylinder and its hydraulic circuit

As can be seen from figure 4.20, the hydraulic circuit of outboard bearing cylinder consists of the pressure reducing valve (35.1), proportional valve (4.1), intermittent valves (42.1) and flow control valves (23.1) from both sides. The pressure reducing valve is used to improve valve operations by stabilizing valve movements and cylinder dynamical properties making them smoother. The proportional valve is used to control the direction of movements and flow control valves are used to control the cylinder's power.
The pressure measurements across the outboard bearing cylinder were done at the points (47.5) and (47.6) which are seen in the hydraulic circuit, figure 4.20 on the right side. The full diagram of the pressure measurements is in figure 4.21.

![Outboard Bearing Cylinder pressure vs time](image)

*Figure 4.21 Pressure measurements of outboard bearing hydraulic cylinder*

The outboard bearing cylinder moves the whole length up once in the beginning starting from 5.526 sec up to 9.125 sec. This movement occurs after the coil is placed on the mandrel and then the cylinder holds the same position within the whole pickling line cycle. The retraction movement of this cylinder takes place at the end when the cylinder returns to the initial position. In this case, no power consumption occurs because the accumulated potential energy of the cylinder is used. This kind of potential energy is the result of gravitational forces acting upon the hydraulic units. The energy is called breaking energy and part of it is transferred directly into the hydraulic line warming up the hydraulic media. It must be dissipated through a cooling procedure.

Strong ripples on the initial part of the pressure curve, figure 4.21, can be the result of some adjustment processes in the hydraulic line due to the high weight of the metal coil in the beginning of the pickling process. Their nature can relate to the pressure decay resistance which is the combination of mechanical factors such as ability to hold position of the load, to seal fluid in hydraulic lines, etc.

![Outboard Bearing Cylinder pressure gradient vs time](image)

*Figure 4.22 Working interval and corresponding pressure gradient of outboard bearing hydraulic cylinder*
Figure 4.22 above describes the performance time of the outboard bearing cylinder. The build up pressure difference on the right side shows that the cylinders’ steady-state pressure for this operation is about 80 bar, and it took some time in the beginning to reach it because there were oscillations within the initial seconds. As a result, the cylinder force transmitted to the load slows down, and within the first second it is not sufficient because the force steady-state level lies above 10 N, figure 4.23.

Figure 4.23 Force and corresponding power of outboard bearing hydraulic cylinder

The maximum power demand of the outboard bearing cylinder is about 20 kW, figure 433-3.

Figure 4.24 Energy consumptions of outboard bearing hydraulic cylinder

The energy graph is used to visualize how the energy discharge takes place. Power is the rate of energy discharge and if it is constant or has just small deviations, figure 4.24, energy discharge graph would look like a straight line revealing the linear nature of energy use. Even though power is quite significant, about 20 kW, but due to the short working time of the hydraulic cylinder, the magnitude of the energy is extremely small, 0.0202 kWh.
4.3.4 Coil diameter measuring system hydraulic cylinder

The coil diameter measuring system includes the hydraulic cylinder which is attached on the left side of the coil storage path. When the middle of the coil is reaching the cylinder, it moves towards it and returns back. Its position data is used to establish the coil size. The stroke length of the cylinder depends on the diameter of the metal coil, maximum is 850 mm.

The bore diameter is 50 mm and from the rod side the diameter is 36 mm. The effective working area from the rod side is 0.002 m$^2$, and from the piston side is 0.0095 m$^2$. The cylinder is fixed and moves just in horizontal directions.

![Image of coil diameter measuring system hydraulic cylinder and its hydraulic circuit](image1)

The pressure measurements across the coil diameter measuring system hydraulic cylinder were done at the points (47.7) and (47.8) which are seen in the hydraulic schematic, figure 4.25. The cylinders hydraulic circuit contains: directional valve (DN 10), pressure reducing valve (33.1), intermittent valves (41.1), flow adjustment valves (22.1).

![Pressure measurements of coil diameter measuring system hydraulic cylinder](image2)

Figure 4.25 Image of coil diameter measuring system hydraulic cylinder and its hydraulic circuit

Figure 4.26 Pressure measurements of coil diameter measuring system hydraulic cylinder
It was identified that the cylinder was used two times within the whole pickling line cycle. The first time was starting from 119.8 sec up to 123.4 sec, and the second time was from 129.3 to 130.69 sec thus totalling 3.6 and 1.39 seconds respectively, figure 4.27. However the disturbance at 200 sec on the pressure measurement curve is the result of the breaking energy transferred into the hydraulic system when the coil diameter measuring cylinder touched the metal coil. This disturbance is not relevant to the power consumptions.

**Figure 4.27 Working intervals of coil diameter measuring system hydraulic cylinder.**

For two times, the cylinder did not perform the same actions, and it can be seen from figure 4.28 that the pressure gradients which were developed across the cylinder were about 8 and 90 bar respectively.

**Figure 4.28 Developed pressure gradient across coil diameter measuring system hydraulic cylinder**
It was assumed that the cylinder was moving at a constant speed of 0.28 m/sec. The force and corresponding power graphs show that for the first time, the force was 1500 N, but second time it was about 3000 N which is two times more. The corresponding power is 0.4 kW and 0.8 kW respectively, figure 4.29. It can be concluded that the cylinder has good dynamical properties because it took about 0.3 sec for it to reach its steady state level of operations in both cases with different loads.

Energy consumptions graphs show that the total energy was 0.000466 kWh and 0.0002961 kWh, figure 4.30.

4.3.5 Double coil storage hydraulic motor

Double coil storage hydraulic motor rotates the metal coil until it achieves the proper starting position to enter the beginning positioning system of the pickling line. The motor is the orbital hydraulic motor of OMR type. It must maintain high starting torque, constant operating torque over the wide speed range, smooth running, and high efficiency [23]. The motors displacement is 160 cm, rotational speed is 80 rev/min. A constant speed of the motor was used for the calculations due
to the insufficiency in the measurements. Image of the motors, and corresponding hydraulic circuit are in figure 4.31.

Figure 4.31 Image of double coil storage hydraulic motor and its hydraulic circuit

The hydraulic circuit of the double coil storage hydraulic motor includes a system of two hydraulic motors in parallel connection. Proportional valve (15.1) is used for directional and flow control in the lines. Two pressure reducing valves serve to improve the dynamical characteristics that can be used as brakes to make a resistance to stop the motors. Two pressure relief valves are used to damp the pressure peaks according to criteria for stopping the motors.

Figure 4.32 Pressure measurements of double coil storage hydraulic motor

As can be seen in figure 4.32, the motors were used two times within the pickling line cycle. The first time was on 329 second up to 338.7 sec, the second was between 573.6 to 582.2 seconds, totally 9.7 and 8.6 seconds respectively, figure 4.33. The strong fluctuations in the pressure
measurements at the end of the pickling line cycle after 1500 seconds are not related to the power consumptions. They can be the result of the load influence.

![Double Coil Storage Hydr. Motor pressure vs time](image1.png)

**Figure 4.33 Working intervals of double coil storage hydraulic motor**

![Double Coil Storage Hydr. Motor Pressure gradient vs time](image2.png)

**Figure 4.34 Developed pressure gradient across double coil storage hydraulic motor**

The pressure gradient looks similar in both cases, figure 4.34. In the beginning, 45 bar of the pressure difference results in high torque, figure 4.35. After this, intervals followed when torque was lowered and ripples existed at the end when the motors stopped.
Energy consumptions of the motors show, figure 4.36, that in the beginning the motors had a higher rate of consumption than at the end. It happened because power was proportional to the torque, and power as the rate of energy use had nonlinear behaviour.

4.3.6 Uncoiler mandrel expansion hydraulic cylinder

The uncoiler mandrel expansion hydraulic cylinder works once in the beginning of the pickling line cycle. It expands the mandrel after the metal coil is placed on it. Depending on the internal coil
diameter the cylinder moves different distances, figure 4.37. The maximum possible stroke length is 0.85 m and the maximum speed is 0.038 m/sec. The rod diameter is 0.1 m and the piston is 0.3 m which makes the effective working area 0.0707 m$^2$, and 0.0628 m$^2$.

Figure 4.37 Image of uncoiler mandrel expansion hydraulic cylinder and its hydraulic circuit

As can be seen in figure 4.37, the hydraulic circuit of the cylinder contains directional valve (1.1), pressure reducing valve (37.1), two flow control valves (50.1), and one special valve (39.1) which can indicate that the cylinder was adjusted to the coil size by sensing a pressure of 100 bar when the expansion was done. Pressure measurements provide information from the ports 47.14 and 47.15.

Figure 4.38 Pressure measurements of uncoiler mandrel expansion hydraulic cylinder

<table>
<thead>
<tr>
<th>Time, sec</th>
<th>Pressure, bar</th>
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<tr>
<td>0-2000</td>
<td>100-150</td>
</tr>
<tr>
<td>2001-4000</td>
<td>150-200</td>
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<td>4001-6000</td>
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<tr>
<td>8001-10000</td>
<td>300-350</td>
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<tr>
<td>10001-12000</td>
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<td>300-350</td>
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<tr>
<td>10001-12000</td>
<td>350-400</td>
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Pressure measurements in figure 4.38 clearly show that from the rod side of the cylinder or from the port (47.15) there are continuous ripples on the pressure curve. There was no energy consumption during this time because the cylinder moved just once in the beginning on the 75th second up to the 77th second of the pickling line cycle. The ripples are the result of the load influence when the metal coil revolves along its axis. At the same time, they indicate how well the cylinder can hold the position and how well the fluid sealing was done.

![Uncoiler Mandrel Expansion Cylinder pressure vs time.](image1)

Figure 4.39 Working interval and pressure gradient across uncoiler mandrel expansion hydraulic cylinder

The pressure difference is not more than 60 bar, figure 4.39, and corresponding force is about 30000 N, figure 4.40.

![Uncoiler Mandrel Expansion Cylinder Force vs Time.](image2)

Figure 4.40 Force and corresponding Power of uncoiler mandrel expansion hydraulic cylinder
Figure 4.41 Energy consumptions of uncoiler mandrel expansion hydraulic cylinder

Energy consumptions of the cylinder is 0.007826 kWh because it is used only for 2 seconds, and power which is needed is exceeding 14 kW.

4.3.7 Strip center guide position hydraulic cylinder

The strip center guide position hydraulic cylinder moves the coil in the horizontal plane according to the position sensor data. The cylinder works continuously through the whole pickling line cycle. The movements are taking any direction depending on the control signal. Forces which are acting are very small. Maximum speed of the cylinder is 0.012 m/sec. The cylinder is called non-differential double-acting hydraulic cylinder because area from both sides is equal due to rod extension from each end. The pressure and flow of the cylinder must be unchanged due to its construction. The calculations were carried out when the cylinder moved in both directions. The effective working area from both ends is 0.0236 m² because the rod is 0.1 m, the bore 0.2 m in diameter, the complete stroke length is 0.3 m.
The hydraulic circuit of the cylinder includes the proportional valve which can change the direction and flow and the small accumulator was integrated to improve the cylindrical movements because the accumulator can provide flow in a fast response manner, figure 4.42.

Pressure measurements reflect the cylinder adjustments through the whole pickling line process, figure 4.43.
4.3.8 Snubber roll adjustment hydraulic cylinder

The snubber roll adjustment hydraulic cylinder is used to take the wheel which would rotate the metal sheet down to the coil, figure 4.45. The maximum speed of the cylinder is 0.2 m/sec, the possible stroke length is 0.85 m. Effective working area is 0.0079 m\(^2\) from the piston side and 0.04 m\(^2\) from the rod side.

Figure 4.45 Image of snubber roll adjustment hydraulic cylinder and its corresponding hydraulic circuit
The hydraulic circuit of the snubbel roll adjustment hydraulic cylinder consists of proportional valve (4.2) which can adjust directions, pressure reducing valve (36.1), flow control valves (23.2) and pilot operated check valves (42.2). Pressure measurements were done in the ports 47.24 and 47.25, figure 4.46.

![Snubber Roll Adjustment Cylinder system pressure vs time.](image)

*Figure 4.46 Pressure measurement of snubber roll adjustment hydraulic cylinder*

The snubber roll adjustment hydraulic cylinder was used only one time during the whole pickling line cycle between 161.6 and 163.48 seconds, totally 1.88 seconds, figure 4.47.

![Snubber Roll Adjustment Cylinder Pressure gradient vs Time.](image)

*Figure 4.47 Working interval and corresponding pressure gradient across snubber roll adjustment hydraulic cylinder*

As can be seen, the pressure gradient in steady state conditions is about 85 bar. The cylinder could reach stability within a few microseconds. Corresponding force and power are 10000 N and 4 kW respectively, figure 4.48.
4.3.9 Snubber roll drive hydraulic motor

The snubber roll drive hydraulic motor rotates the wheel which in turn moves the metal coil by pushing it up further into the pickling line. The motor is the reversible orbital OMR type hydraulic actuator. The motors displacement is 200 cm, speed is 190 rev/min, Figure 4.50.
Hydraulic circuit of the motor starts with pressure reduced valve (31.1), proportional valve (15.2) able to adjust both direction and flow in the lines, and pressure relief valves (26.2). Pressure measurements were done in the ports 47.27 and 47.28, Figure 4.51.

Through analysis of pressure measurements, it was established that the motor worked three times during the pickling line cycle. The first time started from 76.2 up to 78.6 second, the second time 78.7 up to 79.5 sec, and the third time from 159.3 up to 161.8 seconds, which makes 2.4 second, 0.8 second, and 2.5 second respectively, figure 4.52.
The pressure gradient across the motor depends on the load because it is a directly proportional force which must be developed to do the job. The first time pressure gradient was about 90 bar for a very short time to give the motor its starting torque, after that, it reduced gradually with some fluctuations on its way. The second and the third working time the motor had similar working conditions because the pressure gradient was about 130 bar, figure 4.53.
Figure 4.55 Power of snubber roll drive hydraulic motor

Torque and power of the motor is proportional to the pressure difference. The maximum power is 5 kW for the first run, and 7.3 kW for the second and third time, figure 4.54 and 4.55.

Figure 4.56 Energy consumptions of snubber roll drive hydraulic motor

The energy consumption of the hydraulic motor is extremely low as can be seen in figure 4.56, for the first run it is 0.001496 kWh, 0.001537 kWh and 0.004402 kWh for the second and third respectively.

4.3.10 Coil break roll adjustment double system hydraulic cylinder

The coil break roll adjustment double system cylinder bends the metal sheet in the beginning of the pickling line cycle. Depending on the situation on the pickling line, the cylinder can be used a few times. The cylinders’ stroke can vary because the metal sheet may have varying thickness. The maximum speed is 0.138 m/sec, the maximum stroke length is 0.85 m. Effective working area is 0.0123 m² from the piston side, and 0.0059 m² from the rod side, figure 4.57.
Figure 4.57 Image of coil break roll adjustment double system hydraulic cylinder and its hydraulic circuit

The hydraulic circuit of the cylinder shows that it is a double system of the identical hydraulic cylinders in parallel connection. There is proportional valve (1.2) to control the directions, pressure reducing valve (13.1), and two flow control valves (51.1). In order to control this cylinder, pressure must be on both sides of the cylinder. Pressure measurements across the cylinder were done in the ports 47.30 and 47.31, figure 4.58.

Through the analysis of the pressure measurements it was established that the cylinder was used three times within the pickling line cycle. Two times the cylinder was bending metal, and one time it returned into initial position, figure 4.59.
As can be seen from figure 4.59 the first time was from 107 second up to 111, the second was from 119 to 124, and at the end from 1096 to 1100 seconds. The total working time was 4, 5 and 4 seconds respectively.

Pressure difference, which developed across the cylinder, was about 90bar which corresponds to a force of 60000 N. Force graph, figure 4.61, shows that when the cylinder was bending metal, it required a higher pressure difference to apply higher forces.
Figure 4.62 Power of coil break roll adjustment double system hydraulic cylinder

Maximum power was more than 8 kW when the cylinder bent the metal, and about 4 kW when the cylinder returned to the initial position, figure 4.62.

Figure 4.63 Energy consumptions of coil break roll adjustment double system hydraulic cylinder

Energy consumptions of the cylinder were 0.004878 kWh, 0.004346 kWh, and 0.002348 kWh.
4.3.11 Coil peeler traverse hydraulic cylinder

The place of coil peel traverse hydraulic cylinder in the pickling line is to pull up one of the table which is movable and supporting the metal sheet. The cylinder is working after the metal was bended in the pickling line by shifting the table toward metal sheet in a horizontal direction. When the initial part of the metal is going further it moves the table back in a similar way. The cylinder is double-acting and its maximum speed is 0.2 m/sec. It travels the full stroke which is 0.6 m. Effective working area from the piston side is 0.0079 m$^2$, and from the rod side is 0.0047 m$^2$.

![Image of coil peeler traverse hydraulic cylinder and its corresponding hydraulic circuit](image)

Figure 4.64 Image of coil peeler traverse hydraulic cylinder and its corresponding hydraulic circuit

Hydraulic circuit of the cylinder contains proportional valve (4.3) to control directions, two supplementary valves (42.3) to smooth the movements, and two flow control valves (23.3), figure 4.64. Pressure measurements across the cylinder were done in the ports 47.32 and 47.33, figure 4.65.

![Pressure measurements of coil peeler traverse hydraulic cylinder](image)

Figure 4.65 Pressure measurements of coil peeler traverse hydraulic cylinder
The first time when cylinder pushed the table toward coming metal sheet was between 80.6 and 83 seconds, and the second time when it pushed the table back was between 116-118.5 seconds. Totally it worked 2.4 and 2.5 seconds, figure 4.66.

The pressure difference which developed was rising from 50 bar to 100 bar in the first move, and it was 50 bar in the second time.

In both cases the cylinder force was fluctuating around 10000N, and corresponding power was 2kW, figures 4.68 and 4.69.
Energy consumptions of the cylinder are 0.003563 kWh and 0.001277 because in the first case more power required to move the cylinder.
4.3.12 Coil peeler double system hydraulic cylinder

Coil peeler cylinder double cylinder system works together with coil peeler traverse hydraulic cylinder by moving the same table in vertical directions, up and down, unless coil peeler traverse hydraulic cylinder moves the table in horizontal directions. The maximum possible speed of the cylinder is 0.09 m/sec, the stroke is 0.018 m. The effective working area from the piston side is 0.0079 m$^2$, and from the rod side is 0.004 m$^2$, figure 4.71.

Hydraulic circuit includes system of two double-acting cylinders connected in parallel, proportional valve which is controlling directions (4.4), flow control valves (23.4) and intermittent valves (42.4) which are improving performance and reducing leakages in the circuit. Pressure measurements across the cylinder were done in the ports 47.34 and 47.35, figure 4.72.
The cylinder consumed energy just one time when it moved the table up towards the metal sheet. When the cylinder moved down the breaking energy was used and no energy consumptions took place. The time of moving up the table was between 105.5-107.7 seconds, figure 4.73.

As can be seen from figure 4.73 the pressure difference arouse between two cylinder ends up to 50 bar which corresponds force of 80000N and power of 7.2 kW, figure 4.74.
4.3.13 Anti-coil break roll hydraulic cylinder

Anti-coil break roll hydraulic cylinder works together with coil break roll adjustment double system hydraulic cylinder by bending the metal sheet when it is entering the pickling line. The maximum speed of the cylinder is 0.175 m/sec, maximum stroke is 0.35 m. Effective working area is 0.047 m$^2$ from the piston side, and 0.0079 m$^2$ from the rod side. In comparison with other cylinders Anti-coil break roll hydraulic cylinder has bigger working area because it is used to overcome the metal resistance while the metal sheet is bending down, figure 4.76.

Energy consumptions of the cylinder when power is 7.2 kW are 0.003641 kWh because the cylinder works 2.2 seconds.
The anti-coil break roll hydraulic cylinder is of double-acting type, and its hydraulic circuit includes proportional valve (4.5) to control directions, two intermittent valves (42.5) and two flow control valves (23.5). As can be seen from figure 4.77 pressure measurements were done in the ports 47.36 and 47.37.

Analysis of the pressure measurements shows that the cylinder was working two times. The first time was between 1095.5-1095.7 seconds when the cylinder was pressing the metal sheet, the second time was between 1112.2-1114.25 seconds when it came back into initial position, figure 4.78.
Figure 4.78 Working intervals of anti-coil break roll hydraulic cylinder

Pressure difference, figure 4.79, shows that the first time it was around 40 bar, and the second time it was 80 bar which is two times more.

Figure 4.79 Pressure gradient of anti-coil break roll hydraulic cylinder

Force which the cylinder developed was 70000N and 77350N, power was 12 kW and 13.45 kW respectively in relation to the working intervals.

Figure 4.80 Force of anti-coil break roll hydraulic cylinder
Energy consumptions of the anti-coil break roll hydraulic cylinder were 0.003701 kWh and 0.006947 kWh because total time which the cylinder was working 1.8 and 2.05 seconds respectively.

4.3.14 Pinch roll unit double system hydraulic cylinder

Pinch unit double hydraulic cylinder is used to move the feeders up and down in vertical directions. The feeders are the combination of rolls which are driving by electrical motors and pushing the metal sheet in the pickling line, figure 4.83. Maximum speed of the cylinder is 0.065 in [m/sec], the stroke is 0.22 m. Effective working area is 0.0254 m² from the piston side and 0.0159 m² from the rod side.
As can be seen from the hydraulic circuit pinch roll unit double hydraulic cylinder is a system of two double-acting hydraulic cylinders which are connected in parallel. There are proportional valve (1.3) to control directions, and two flow control valves (51.2). Pressure measurements were done in the ports 47.39 and 47.40, figure 4.84.

Within the pickling line cycle pinch unit double hydraulic cylinder was used ones between 1085.2-1089.3 seconds when it moved into initial position, figure 4.86. It happened, that when the cylinder moved the feeder in the beginning of the pickling line cycle it was used its kinetic energy due to gravitational forces acting upon the feeder.
There are fluctuations on the pressure curve in the beginning when the cylinder started to work. The pressure raised from 10 bar to 20 bar, and remained 20 bar for the rest of the work, figure 4.85.

The force was 40360 N and the power 2.577 kW which lead to the 0.002467 kWh of total energy consumptions, figure 4.86.

Figure 4.85 Working interval and pressure gradient across pinch roll unit double hydraulic cylinder

Figure 4.86 Force and power of pinch roll unit double hydraulic cylinder

Figure 4.87 Energy consumptions of pinch roll unit double hydraulic cylinder
4.3.15 Top roll adjustment double system hydraulic cylinder

Top roll adjustment double system hydraulic cylinder is used in the same way as pinch unit double hydraulic cylinder because it is also leaning the feeders up and down in vertical directions, figure 4.88. The maximum possible speed of the cylinder is 0.065 m/sec, the stroke is 0.22 m. Effective working area is 0.0254 m$^2$ from the piston side and 0.0159 m$^2$ from the rod side.

![Image of top roll adjustment double system hydraulic cylinder and its hydraulic circuit](image)

Figure 4.88 Image of top roll adjustment double system hydraulic cylinder and its hydraulic circuit

Hydraulic circuit of the cylinder includes two double-acting cylinders in parallel connection, proportional valve to control directions (1.4), flow control valves (51.3), and flow control valves in the vicinity of the cylinders rod to adjust flow with higher precision. Pressure measurements were done in the ports 47.41 and 47.42, figure 4.89.

![Experiment 5. Hydraulic cylinder 2 system pressure](image)

Figure 4.89 Pressure measurements of top roll adjustment double system hydraulic cylinder
Totally during the pickling line cycle the cylinder worked two times, but in the beginning when it was leaning the feeder no power consumptions occur due to kinetic energy of the feeder. At the end of the pickling cycle there was energy demand when the cylinder moved up into its initial position.

**Figure 4.90 Working interval and corresponding pressure gradient of top roll adjustment double system hydraulic cylinder**

Pressure difference which developed between cylinder ends was 21 bar when the cylinder was lifted into initial position, corresponding force was 60000N and power 4 kW, figure 4.91.

**Figure 4.91 Force and power of top roll adjustment double system hydraulic cylinder**
Energy consumptions of top roll adjustment double system hydraulic cylinder were 0.003534 kWh because the cylinder worked only 2.5 seconds.

4.3.16 Cutting hydraulic cylinder

Cutting hydraulic cylinder is used in the pickling line to cut the metal sheet after its thickness was examined. If the thickness is more than acceptable or some deformations occurred with the metal the part of the metal sheet must be removed from the coil. Within the pickling line cycle the cylinder can work many times until proper part of the metal coil would not be reached. As can be seen from figure 4.316-1 cutting hydraulic cylinder is quite big in comparison with others hydraulic actuators. Effective working area is 0.0804 m² form the piston side and 0.0424 m² from the rod side, figure 4.93.
Hydraulic circuit of cutting cylinder includes proportional valve (16.1) which is capable to control both direction and flow, two pilot operated check valves (78.1 and 44.1) to improve performance, additional proportional valve (7.1) to control directions. Pressure measurements were done in the ports 47.83 and 47.84, figure 4.94.

![Experiment 5. Hydraulic cylinder 3 system pressure](image)

Figure 4.94 Pressure measurements of cutting hydraulic cylinder

Pressure measurements analysis shows that cutting hydraulic cylinder was used nine times within the pickling line cycle. Figure 4.95 contains the fragments when the cylinder was working.
Pressure difference, figure 4.96, is quite high in all nine cases, and the number of 140 bar is realistic average for all working intervals.
Figure 4.96 Pressure gradient of cutting hydraulic cylinder
The force of the hydraulic cylinder is proportional to the pressure difference and effective area. As can be seen from figure 4.97, in most of the cases force was around 1000000N or two times less 500000N. Corresponding power is 80 kW and 40 kW. This makes cutting hydraulic cylinder the biggest power consumptions hydraulic unit in the pickling line.
Figure 4.98 Power of cutting hydraulic cylinder and its hydraulic circuit
For each working interval, figure 4.100, energy consumptions were calculated separately. Table 4.1 contains the information of total working time and what was the energy demand. In comparison with others hydraulic cylinders, cutting cylinder worked slightly longer and spent more energy.
Table 4.1 Energy consumptions of cutting hydraulic cylinder

<table>
<thead>
<tr>
<th>Working interval, seconds</th>
<th>Total time, seconds</th>
<th>Force, N</th>
<th>Power, kW</th>
<th>Energy consumptions, kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>Stop</td>
<td>1100000</td>
<td>80</td>
<td>0.1073</td>
</tr>
<tr>
<td>212.8</td>
<td>218.1</td>
<td>1100000</td>
<td>80</td>
<td>0.1073</td>
</tr>
<tr>
<td>218.1</td>
<td>225.9</td>
<td>1100000</td>
<td>80</td>
<td>0.1073</td>
</tr>
<tr>
<td>225.9</td>
<td>231.2</td>
<td>1050000</td>
<td>80</td>
<td>0.1268</td>
</tr>
<tr>
<td>1126.2</td>
<td>1133.8</td>
<td>500000</td>
<td>36</td>
<td>0.04543</td>
</tr>
<tr>
<td>1133.8</td>
<td>1139.5</td>
<td>1100000</td>
<td>80</td>
<td>0.1175</td>
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<td>483000</td>
<td>35</td>
<td>0.002288</td>
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<tr>
<td>1168.9</td>
<td>1172</td>
<td>1030000</td>
<td>76</td>
<td>0.0615</td>
</tr>
</tbody>
</table>

Energy consumptions of the whole cutting process are 0.690887 kWh.

4.3.17 Side guides hydraulic cylinder

The place of side guides double system hydraulic cylinder is after and beneath top roll adjustment double system and pinch roll unit double hydraulic cylinders. When this two cylinders lowering the feeder the metal sheet is moving further through side guides double system hydraulic cylinder which is aligning the sheet, figure 4.100. The maximum speed of the cylinder is 0.29 m/sec, the stroke is 0.65 m. Effective working area from the piston side is 0.0314, and from the rod side is 0.0236.

Figure 4.100 Image of side guides hydraulic cylinder and its hydraulic circuit

Side guides hydraulic cylinder is double-acting cylinder which is controlling by valve combinations. Proportional valve (14.1) is used to control directions and flow, pressure reducing valve (35.3) to adjust pressure, two pilot operated check valves (80.1) to control the load, and
pressure relieve valve (30.3). Pressure measurements were done in the ports 47.46 and 47.47, figure 4.101.

Figure 4.101 Pressure measurements of side guides hydraulic cylinder

Pressure measurements analysis could show that the cylinder used two times during the pickling line cycle. The first time was between 138.32-142.68 seconds, and the second time was between 150.05-154.58 seconds. The durations were 4.36 and 4.53 seconds respectively, figure 4.102.

Figure 4.102 Working intervals of side guides hydraulic cylinder
Pressure difference across side guides hydraulic cylinder was 80 bar in steady state conditions, Figure 4.103. Corresponding force was equal to 1500000N, and power to 70 kW in both cases.

Figure 4.104 Force and power of side guides hydraulic cylinder
Power demand of side guide hydraulic cylinder was 70 kW which lead to relatively high energy consumptions in comparison with others hydraulic cylinders of similar kind, equal to 0.05936 and 0.08048 kWh.

4.3.18 Flattener double system hydraulic cylinder

Flattener double system hydraulic cylinder is responsible to move leveling machine. Leveling machine has few rolls which can press and push further the metal sheet. The task of the cylinder is to lower the leveling machine when the metal sheet is reaching its location, and lift it back into initial position at the end of the pickling cycle, figure 4.106. Maximum speed of the cylinder is 0.05 m/sec, the stroke is 0.35 m. Effective working area from the piston side is 0.0314 m$^2$, and from the rod side is 0.0236 m$^2$.
Hydraulic circuit of flattener double system hydraulic cylinder consists of a system of two double-acting hydraulic cylinders connected in parallel and a valve combination to control them. There is no adjustments of the flow rate in the line just one pilot operated directional valve is used. Pressure measurements of the cylinder were done in the ports 47.48 and 47.49, figure 4.107.

Pressure measurements analysis shows that the cylinder required to use energy at the end of the pickling line cycle between 1117.8-1123.4 second because in the beginning the lowering of the leveling machine was done by using its kinetic energy due to gravitational forces acting upon it.

As can be seen from the figure above the maximum pressure gradient is 17 bar which leads to the force of 70000N and power demand less than 5kW, figures 4.108 and 4.109.
The energy consumptions if the flattener double system hydraulic cylinder were 0.004559 kWh because it was active very short time 5.6 seconds and its power consumptions were less than 5 kW.

### 4.3.19 Strip stabilizing rolls double system hydraulic cylinder

Strip stabilizing rolls double system hydraulic cylinder is used when the metal sheet already passed the leveling machine for further adjustments before metal cutting, figure 4.111. The maximum possible speed of the cylinder is 0.06 m/sec, the stroke is 0.125 m. Effective working area is 0.0026 m² from the piston side and 0.005 from the rod side.
Hydraulic circuit of the cylinder contains a system of two double-acting cylinders connected in parallel. There is proportional valve to adjust directions (6.2), pilot operated check valves (41.2), flow control valves located in the vicinity of the cylinders from both ends (57.2 and 57.4) capable to control flow and speed of the cylinder. Pressure measurements were done in the ports 47.50 and 47.51, figure 4.112.

Pressure measurements analysis gives the information that the cylinder required power when it was moving up between 200.3-201 second, figure 4.113.
Figure 4.113 Working intervals and pressure gradient of strip stabilizing rolls double system hydraulic cylinder.

As can be seen from figure 4.114 pressure difference was 40 bar which means that calculated force is 20000N and required power is 0.2 kW, figure 4.114.

Figure 4.114 Force and power of strip stabilizing rolls double system hydraulic cylinder
Energy consumptions of strip stabilizing rolls double system hydraulic cylinder are 0.0001567 kWh.

4.3.20 Top roll drive hydraulic motor

Top roll drive hydraulic motor is a part of feeding 2 and it is feeding the metal sheet through the cutting part of the pickling line system. The motor in this location is additional torque component for the safety reasons, due to that it is not consuming energy intensively, figure 4.117. The motor is OMR orbital type with high starting torque and smooth running. The motors displacement is 200, speed is 190 rev/min.
Hydraulic circuit of top roll drive hydraulic motor includes pressure reduced valve (31.2), proportional valve (4.2) to control flow and directions, pressure relieve valves (26.3). Pressure measurements of the hydraulic motor were done in the ports 47.52 and 47.53, figure 4.117.

![Figure 4.117 Pressure measurements of top roll drive hydraulic motor](image)

**Figure 4.117 Pressure measurements of top roll drive hydraulic motor**

As can be seen from figure 4.118 top roll drive hydraulic motor was working two times within the pickling line cycle. The first time was between 209-213 seconds, the second 1141.5-1149 seconds.

![Figure 4.118 Working intervals of top roll drive hydraulic motor](image)

**Figure 4.118 Working intervals of top roll drive hydraulic motor**
The pressure difference which developed between two motors ports shows, figure 4.119 that each time in the beginning there was high starting torque, and with the time it faded down affected by ripples.

Motors torque curve looks similar to pressure gradient representation due to direct relation. Torque was 350 Nm and 100 Nm respectively, figure 4.120.
Figure 4.121 Power of top roll drive hydraulic motor

Power which required to run the motor depending on the torque. In the first case it is 7 kW, and in the second case it is 2 kW. Torque and power are directly proportional to the load. The difference between two working intervals tells that the load was not similar in the cases.

Figure 4.122 Power of top roll drive hydraulic motor

Energy consumptions of top roll drive hydraulic motor were 0.005252 kWh and 0.001701 kWh. Figure 4.122 reflects non-linear behavior of the motor power in the last working time.

4.3.21 Top roll adjustment hydraulic cylinder

Top roll adjustment hydraulic cylinder is lowering down feeders-2 which has one roll to press and push the metal sheet toward cutting area. Maximum speed of the cylinder is 0.2 m/sec, the stroke is 0.63 m. The cylinder moves the full stroke distance in order to put feeders 2 into proper position. Effective working area of the cylinder from its piston side is 0.005 m², and from its rod side is 0.0026 m².
Hydraulic circuit of top roll adjustment hydraulic cylinder includes proportional valve (3.1) to control directions, pressure reduced valve (36.2), and two flow control valves (23.6). Pressure measurements were done in the ports 47.54 and 47.55, figure 4.123 and 4.124.

Top roll adjustment hydraulic cylinder spent power one time when it was lifting up feeders-2, otherwise it used kinetic energy of the feeders-2. The time interval is starting from 1127 to 1130.5 seconds, figure 4.125.
Figure 4.125 Working interval and pressure gradient of top roll adjustment hydraulic cylinder

Pressure gradient was 40 bar which leads to the force not more than 50000N and required power of 1kW, figure 4.126.

Figure 4.126 Force and power of top roll adjustment hydraulic cylinder
Figure 4.127 Pressure measurements of top roll adjustment hydraulic cylinder.

Energy consumptions of top roll adjustment hydraulic cylinder were 0.0004736 kWh.

4.3.22 Sampling device double system hydraulic cylinder

Sampling device double system hydraulic cylinder is used to hold and move hinged table. Hinged table is a part of the cutting device and supports the metal sheet under certain angle while it is being cut, figure 4.128. Maximum cylinder speed is 0.1m/sec, the stroke is 0.155 m. Effective working area is 0.002 m$^2$ from the piston side and 0.0009 from the rod side.

Figure 4.128 Image of sampling device double system hydraulic cylinder and its hydraulic circuit
Hydraulic circuit of the cylinder includes two double-acting hydraulic cylinders connected in parallel, proportional valve (6.4) to control directions, two pilot operated check valves (41.4), and two flow control valves (22.3). Pressure measurements were done in the ports 47.59 and 47.60.

Experiment 7. Hydraulic cylinder 3 system pressure

Figure 4.129 Pressure measurements of sampling device double system hydraulic cylinder

Analysis of the pressure measurements gives information that the hinged table was moved two times when there were energy consumptions, figure 4.130.

Figure 4.130 Working intervals of sampling device double system hydraulic cylinder
Pressure gradient tells that the pressure difference in both cases was 20 bar which corresponds force of 30000N and power of 3 kW.
4.3.23 Cutting DS-1 and DS-2 hydraulic cylinders

Cutting DS-1 and DS-2 hydraulic cylinders are used to cut edges ones on the both sides of the metal sheet before entering acid bath of the pickling line. The cylinders are identical their maximum speed is 0.05 m/sec, the stroke is 0.15 m. Effective working area from the piston sides is 0.0707 m$^2$, and from the rod sides is 0.0452 m$^2$. 

Energy consumptions of sampling device double system hydraulic cylinder are 0.001267 kWh and 0.000679 kWh.
Figure 4.134 Hydraulic circuit of cutting DS-1 hydraulic cylinder on the left and cutting DS-2 on the right side

Hydraulic connections of both cutting DS-1 and DS-2 hydraulic cylinders are similar. They include proportional valves (2.1 and 2.2), pilot operated check valves (43.1 and 43.2), flow control valves (51.4 and 51.5). For the simplification pressure measurements were done just for one cutting DS hydraulic cylinder in the ports 47.85 and 47.86, figure 4.135.

Figure 4.135 Pressure measurements of cutting DS-type hydraulic cylinder
Analysis of the pressure measurements shows that the cylinder worked two times. The first time was between 277.4-279 seconds, and the second was between 281-282.7 seconds, which makes it totally 1.6 and 1.7 seconds, figure 4.136.

![Figure 4.136 Working intervals of cutting DS-type hydraulic cylinder](image1)

![Figure 4.137 Pressure gradient across cutting DS-type hydraulic cylinder](image2)

As can be seen from figure 4.138 pressure gradient was 20 bar and 80 bar because it depended on the load which the cylinder must handle.
Figure 4.138 Force and power of cutting DS-type hydraulic cylinder

Corresponding calculated force and pressure show that in the first case the force was 150000N and the power was 13 kW, the second time the force was 230000N and the power was 25 kW.

Figure 4.139 Energy consumptions of cutting DS-type hydraulic cylinder
Energy consumptions of the cutting DS-1 hydraulic cylinder were 0.01234 kWh, and of the cutting DS-2 were 0.009464 kWh.

4.3.24 Traverse drive cutting tool DS-1 hydraulic cylinder

Traverse drive cutting tool DS-1 hydraulic cylinder is moving towards the coming metal sheet cutting DS-1 hydraulic cylinder. The movements of the cylinder are happening in horizontal directions, back and force. The maximum speed of the cylinder is 0.2 m/sec, the stroke is 0.95 m. Effective working area is 0.005 m$^2$ from the piston side, and 0.0026 m$^2$ from the rod side.

Figure 4.140 Hydraulic circuit of traverse drive cutting tool DS-1 hydraulic cylinder

Hydraulic circuit of traverse drive cutting tool DS-1 hydraulic cylinder, figure 4.140, consists of proportional valve (18.1) which is capable to adjust flow and directions in the line. Pressure measurements across the cylinder were done in the ports 47.89 and 47.90, figure 4.141.
Figure 4.141 Pressure measurements of traverse drive cutting tool DS-1 hydraulic cylinder

The pressure measurement analysis shows that the cylinder moved two times. The first time was between 273-275.6, the second was between 282.5-284.5 which makes it totally 2.6 and 2 seconds respectively.

Figure 4.142 Working intervals of traverse drive cutting tool DS-1 hydraulic cylinder

Figure 4.143 Pressure gradient across traverse drive cutting tool DS-1 hydraulic cylinder
Pressure gradient developed between cylinders ends was 95 bar and 7 bar depending on the load, figure 4.143.

The forces which correspond to 95 bar pressure difference are 55000N and to 7 bar are 10000N. Power is 11 kW and 3 kW respectively.
Energy consumptions of the traverse drive cutting tool DS-1 hydraulic cylinder were 0.007644 kWh and 0.0006791 kWh.

**4.3.25 Traverse drive cutting tool DS-2 hydraulic cylinder**

Traverse drive cutting tool DS-2 hydraulic cylinder is moving towards the coming metal sheet cutting DS-2 hydraulic cylinder. The movements of the cylinder are happening in horizontal directions, back and force. The maximum speed of the cylinder is 0.2 m/sec, the stroke is 0.95 m. Effective working area is 0.005 m² from the piston side, and 0.0026 m² from the rod side.
Hydraulic circuit of traverse drive cutting tool DS-2 hydraulic cylinder, figure 4.146, consists of proportional valve (18.1) which is capable to adjust flow and directions in the line. Pressure measurements across the cylinder were done in the ports 47.91 and 47.92, figure 4.147.
The pressure measurement analysis shows that the cylinder moved two times. The first time was between 273-275, the second was between 282.4-284.3 which makes it totally 2 and 1.9 seconds respectively.

Pressure gradient developed across the hydraulic cylinder in the first case was 103 bar and in second was 13.5 bar.
The cylinder force which is corresponding pressure gradient of 103 bar is 56000 N and the power is 11.5 kW, the force which is corresponding 14 bar is 7600N and power is 1.55 kW

Figure 4.149 Pressure gradient across traverse drive cutting tool DS-2 hydraulic cylinder

Figure 4.150 Force and power of traverse drive cutting tool DS-1 hydraulic cylinder
4.3.26 Side guides-2 hydraulic cylinder

Side guides-2 hydraulic cylinder is located before the acid bath and its task is to center the metal sheet and remain in that position the rest of pickling line cycle. The maximum speed of the cylinder is 0.2 m/sec, the stroke is 0.65 m. The effective working area is 0.0031 m\(^2\) from the piston side and 0.0015 m\(^2\) from the rod side.
Hydraulic circuit of side guides-2 hydraulic cylinder consists of proportional valve (14.3) to control flow and directions, pressure relieve valve (30.4). Pressure measurements across the cylinder were done in the ports 47.93 and 47.94, figure 4.152 and 4.153.
The pressure measurements analysis shows that the cylinder worked one time starting from 269 up to 270.8 seconds, figure 4.154.

**Figure 4.153 Pressure measurements of side guides-2 hydraulic cylinder**

**Figure 4.154 Working interval and pressure gradient of side guides-2 hydraulic cylinder**
Pressure gradient was 13 bar and corresponding force and power were 800 N and 1.6 kW respectively.

The side guides-2 hydraulic cylinder energy consumptions are 0.0007277 kWh.
4.4. Performance estimation of the initial part pickling line hydraulic system.

Performance of the initial part pickling line hydraulic system can be estimated through the analysis of two important parameters: the first one is the required power to run the hydraulic units and the second one is the corresponding consumed energy while the power was applied. Power is reflecting mechanical forces needed to operate the pickling line. The hydraulic line power consumptions are shown in figure 4.157.

As can be seen from the power consumptions graph, within one pickling line cycle the power consumptions are not distributed evenly over the whole time range. They are clocked together in the beginning and at the end of the cycle. It happened because the power to move hydraulic actuators was needed for the initial adjustments of the metal coil in the line and at the end when the hydraulic actuators returned to their starting positions to get ready for processing the next metal coil. The maximum power magnitude is 90 kW.

The energy which was consumed by the initial part pickling line hydraulic system can be calculated with a very high precision. This is because the thorough analysis of the hydraulic units through their pressure measurements in chapter 4.3 enabled detailed energy consumption calculations. A summary of the consumed energy over the whole pickling line cycle in table 4.2 is given.
Table 4.2 The initial part pickling line hydraulic system energy consumptions within one pickling line cycle.

<table>
<thead>
<tr>
<th>Number</th>
<th>Hydraulic Unit</th>
<th>Consumed Energy, kWh</th>
<th>Port A</th>
<th>Port B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Press Roll Driving Motor</td>
<td>0.05358</td>
<td>6.1</td>
<td>6.2</td>
</tr>
<tr>
<td>2</td>
<td>Press Roll Cylinder</td>
<td>0.0034268</td>
<td>6.3</td>
<td>6.4</td>
</tr>
<tr>
<td>3</td>
<td>Outboard Bearing Cylinder</td>
<td>0.0202</td>
<td>47.5</td>
<td>47.6</td>
</tr>
<tr>
<td>4</td>
<td>Coil Diameter Measuring Cylinder</td>
<td>0.0007519</td>
<td>47.7</td>
<td>47.8</td>
</tr>
<tr>
<td>5</td>
<td>Double Coil Storage Motor</td>
<td>0.0019282</td>
<td>47.9</td>
<td>47.1</td>
</tr>
<tr>
<td>6</td>
<td>Uncoiler Mandrel Expansion Cylinder</td>
<td>0.007826</td>
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<td>47.15</td>
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<tr>
<td>7</td>
<td>Strip Center Guide Position Cylinder</td>
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<td>8</td>
<td>Snubber Roll Adjustment Cylinder</td>
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<td>Snubber Roll Drive Motor</td>
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<td>11</td>
<td>Coil Peeler Traverse Cylinder</td>
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<td>Coil Peeler Double System Cylinder</td>
<td>0.003641</td>
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<tr>
<td>13</td>
<td>Anti-coil Break Roll Cylinder</td>
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<tr>
<td>14</td>
<td>Pinch Unit Double System Cylinder</td>
<td>0.005741</td>
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<td>Top Roll Adjustment Double System Cylinder</td>
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<tr>
<td>25</td>
<td>Traverse Drive Cutting Tool DS-1 Cylinder</td>
<td>0.0085231</td>
<td>47.89</td>
<td>47.9</td>
</tr>
<tr>
<td>26</td>
<td>Traverse Drive Cutting Tool DS-2 Cylinder</td>
<td>0.0066898</td>
<td>47.91</td>
<td>47.92</td>
</tr>
<tr>
<td>27</td>
<td>Side Guides-2 Cylinder</td>
<td>0.0007277</td>
<td>47.93</td>
<td>47.94</td>
</tr>
</tbody>
</table>

The energy consumptions of each hydraulic unit can be summed up and thus the resulting total energy consumed by the initial part Pickling line hydraulic system is 1.0575 kWh.

4.5 Performance estimation of the Electrical Motors.

The five electrical motors of ASEA (ABB) Group run the hydraulic pumps continuously to meet the energy demand of the initial part Pickling line hydraulic system. The electrical motors'
performance can be evaluated through the analysis of the current measurements which were done for each of the motors separately. An image of the electrical motors and pumps and their corresponding hydraulic circuit is shown in figure 4.158.

The motors which are shown in figure 4.158 are running hydraulic pumps which have direct hydraulic connections into the common high pressure line of the hydraulic system. These motors are P1, P2, P3 and P4. Only one electrical motor P6 is supplying energy into the hydraulic pump which is connected to the Cooling system of the initial part pickling line hydraulic system and it is shown in figure 4.159.
All motors have similar technical parameters: the voltage is 500 V, the rotational speed is 380 rotations per minute and \( \cos \phi \) is equal to 0.83. The power which the electrical motors are delivering into the hydraulic system is directly proportional to the current consumptions.

The motor’s power \( P_{el} \) was calculated by using equation 12:

\[
P_{el} = \sqrt{3} I \times U \cos \phi \times \eta
\]  

(12)

Where \( I \) is the electrical motor current measured in [A], \( U \) is the voltage [V], \( \cos \phi \) is the power factor and \( \eta \) is the motors efficiency.

The energy \( E_{el} \) delivered by the motor was calculated by using equation 13:

\[
E_{el} = P_{el} \times \frac{\Delta t}{3600}
\]

(13)

Where, \( \Delta t \) is the time step.

In the first step of data processing, the power delivered by each electrical motor was calculated individually and the graphs for them can be found in Appendix A. The delivered power of the electrical motor is proportional to the current consumptions and to the motor’s efficiency as shown in figure 4.160.

![Figure 4.160 Current measurements and calculated power of P3 electrical motor](image)

The statistical information about delivered power by electrical motors is shown in table 4.3.
Table 4.3 Power and energy delivered by each electrical motor individually

<table>
<thead>
<tr>
<th>Motors</th>
<th>Mean Power, kW</th>
<th>Minimum Power, kW</th>
<th>Maximum Power, kW</th>
<th>Standard Deviation</th>
<th>Energy, kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>17.0212</td>
<td>16.1215</td>
<td>32.4037</td>
<td>1.4418</td>
<td>5.679</td>
</tr>
<tr>
<td>P2</td>
<td>18.4832</td>
<td>17.5064</td>
<td>33.9569</td>
<td>1.6682</td>
<td>6.143</td>
</tr>
<tr>
<td>P3</td>
<td>18.3312</td>
<td>16.4659</td>
<td>34.0335</td>
<td>1.0843</td>
<td>6.116</td>
</tr>
<tr>
<td>P4</td>
<td>31.0673</td>
<td>26.887</td>
<td>35.9922</td>
<td>1.7967</td>
<td>9.356</td>
</tr>
<tr>
<td>P6</td>
<td>15.2049</td>
<td>14.2469</td>
<td>31.8681</td>
<td>1.5869</td>
<td>5.002</td>
</tr>
</tbody>
</table>

As can be seen in table 4.3, the mean of the maximum power is 34 kW.

During the second step of data processing, the delivered power by five electrical motors was integrated and the resulting graph is shown in figure 4.161

As can be seen from figure 4.161, the maximum power which was delivered to the hydraulic system was 155 kW. It can be observed that the power histogram representation does not represent normal distribution. Instead, this graph is squashed to the left side towards power consumptions of 90 kW. Also, there are a very small number of events related to power consumptions of more than 100 kW. The main statistical data is shown in table 4.4.

Table 4.4 Power delivered by electrical motors simultaneously

<table>
<thead>
<tr>
<th>Mean Power, kW</th>
<th>Minimum Power, kW</th>
<th>Maximum Power, kW</th>
<th>Standard Deviation</th>
<th>Energy, kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>95.9558</td>
<td>90.9446</td>
<td>155.0557</td>
<td>8.4324</td>
<td>32.02</td>
</tr>
</tbody>
</table>

The total energy which was delivered into the initial part Pickling line hydraulic system was calculated by integration of the energies delivered by each electrical motor. The total energy delivery is shown in figure 4.162, and it is equal 32.05 kWh.
**4.6 Energy efficiency evaluation**

The energy efficiency can be defined as the ratio between useful output of a system and the energy input into the system. There is a set of energy efficiency coefficients proposed for the steel industries to measure the effectiveness of their production lines or manufacturing processes. These energy efficiency coefficients are Specific Energy Consumptions (SEC) and Energy Efficiency Index (EEI) [4]. SEC is one of the energy efficiency indicators which measures the energy efficiency of different processes looking into the relation between energy being used and the product being produced. EEI is used to monitor the progress of energy efficiency reflected by SEC. The initial part of the pickling line hydraulic system is integrated into overall production capabilities of the SSAB steel plant. The energy efficiency which is calculated in the thesis is relevant for only a tiny component of the whole production layout at SSAB.

The energy efficiency would be defined as a ratio between the total energy which was consumed by the initial part pickling line hydraulic system within one full pickling line cycle and the total energy which was produced by the induction electrical motor driven pump sets as shown in equation 14.

\[
E_{\text{EFF}} = \frac{E_{\text{HYDR}}}{E_{\text{PUMP}}} \tag{14}
\]

Where, \( E_{\text{EFF}} \) is the total energy efficiency, \( E_{\text{HYDR}} \) is the energy consumed by the hydraulic system and \( E_{\text{PUMP}} \) is the energy delivered to the system by the electrical motors and pumps combination.

The energy consumptions of the initial part pickling line hydraulic system were found with high precision when at first the energy consumptions of each hydraulic component were calculated separately and secondly when they were summed up over the whole pickling line cycle. The
delivered energy is the indicator of the input into the hydraulic system by electrical motors and pump combination when efficiencies of motors were considered.

Thus the total energy efficiency of the initial part pickling line hydraulic system is:

$$E_{EFF} = \frac{1.0575}{32.05} = 0.3299 = 3.3\%$$

The calculations of the total energy efficiency showed, that only 3.3% of the energy, which was delivered into the initial part pickling line hydraulic system, was used by hydraulic components and the rest of the energy was converted into heat and lost by the system.
5. System analysis and optimization

5.1 System analysis

The initial part pickling line system can be viewed as one entire system with two major subsystems as shown in figure 5.1. The first subsystem is the induction motor-driven high-energy pump sets and the second subsystem includes the open-loop high pressure hydraulic system with the oil storage tank, cooling facilities and hydraulic units.

![Figure 5.1 Structure of the initial part pickling line hydraulic system](image)

A total of five electrical motors of nominal power 37 kW operate axial variable displacement pumps which are delivering 120 l/min flow by working continuously and transferring energy into the hydraulic part of the system where the desired system pressure is 160 bar and mineral oil is used as a hydraulic media.

The energy distribution in the initial part pickling line hydraulic system demonstrates “Direct Energy Flow” because all the electrical energy which is being converted into hydraulic form by the induction motor-driven pumps, flow directly to the hydraulic circuit to provide the ability for the hydraulic actuators to do the work as shown in figure 5.2.

![Figure 5.2 Direct energy flow between subsystems](image)
The current structure of the initial part pickling line hydraulic system has no advanced control over the energy distribution as there are no flow adjustment solutions in the system. Only the valves can be used to restrict the flow intensities. The motor-driven pump sets are continuously delivering energy regardless of the demand from the hydraulic units thus creating a situation where the energy excess is triggering a higher oil temperature and eventually this energy is being lost by the system.

The comparison between the subsystems within the initial part pickling line hydraulic system can be made by looking into the hydraulic system power demand and motor-driven pumps sets power delivery which is shown in figure 5.3.

![Figure 5.3 Power consumptions comparison](image)

The maximum power demand of the hydraulic system was not more than 90 kW but the motor-driven pump sets were capable to deliver a maximum of 160 kW of power. When there was no power consumption by the hydraulic units, the motor-driven pump sets continuously delivered 95 kW throughout the whole pickling line cycle and the system was operated in a continually throttled mode. The energy efficiency analysis shows that the design of the system was not optimal and as a result the system was extremely oversized which in turn gave a poor energy efficiency of 3.3 % as it was proven in chapter 4.6 of the thesis work.
5.2 The initial part pickling line hydraulic system possible modernizations and energy savings

5.2.1 Conventional hydraulic systems versus modern solutions

The design of the industrial system was oriented towards handling the worst-case upset conditions and excess of the flow was controlled by throttling valves and dampers. The exact power demand was not matched with the system output and the recirculation in by-pass loops was used in periods where there was no need for flow in the system.

Nowadays, new technologies are capable enough to be fitted into the hydraulic system to improve working abilities. They are designed to enable the system to meet the exact load demand. Hydraulic accumulators, feedback control, variable speed drives, and advances in valves technology are the main examples of such technologies.

Systems resizing would help to reduce energy demand of the industrial hydraulic systems which would open the door for renewable energy sources to become a part of the industrial energy supply chain.

5.2.2 Hydraulic accumulators

The hydraulic accumulators are devices which are storing potential energy which is hidden in the hydraulic pressure in the lines of the hydraulic systems. Hydraulic accumulators can be of different types. Some examples include weight-loaded accumulators, spring-loaded, hydro-loaded and piston type accumulators. The piston type of the hydraulic accumulators consists of a cylinder body and a movable piston with resilient seals which is shown in figure 5.4. Gas occupies the volume above the piston and becomes compressed when the cylinder body is charged with fluid. When the fluid flows from the accumulator, the pressure of the gas is decreases.

In this way, the hydraulic accumulators can perform energy saving functions in the hydraulic circuits because they can maintain stable system pressure and supplement the pump flow rate thus absorbing sudden system shocks.
One of the important applications of the hydraulic accumulators is to deliver flow into the hydraulic system when it needs to do the work or when it is necessary to compensate the system internal leakages. The accumulators would deliver flow into the hydraulic system just in case the pump flow is not enough to do the operations.

In case the hydraulic accumulators would be integrated into the existing initial part pickling line hydraulic system, they would change the energy distribution within the system by making it of an “Indirect Energy Flow” type as shown in figure 5.5.

![Indirect Energy Flow](image)

**Figure 5.5 Indirect energy flow between subsystems**

### 5.2.2 Control options and programmable valves

The hydraulic systems can be controlled through valve operations. As it was described in chapter 4.2 of the thesis work, there are three main parameters in the hydraulic systems which must be observed: flow rate, flow directions and pressure. New energy-saving programmable valves along with intelligent control development can significantly improve the performance of hydraulic lines.

The set of programmable valves integrated into the hydraulic system can independently control each hydraulic unit state as well as providing fully controlled regeneration flow for maximum energy saving and simultaneous precise motions tracking [25].

### 5.2.2 High-efficient electric motors

In hydraulic systems, each component has its own efficiency. Energy savings due to a high overall system efficiency may be possible when the components operate at their maximum efficiency points.

Electrical motors can have better efficiency if the motor losses would be reduced. There are three types of motors accordingly to IEC standards which are high-efficiency motors: improved efficiency motors and high-efficiency motors. Thus high-efficiency motors can produce the same mechanical output power as standard efficiency motors. Some of the improvements of high-efficiency motors
are better rotor and stator design, improved material properties, special insulation and many other improved characteristics [26].

### 5.2.3 Variable speed drives.

New constructed hydraulic systems can make adjustments of the pump delivery by intelligently modulating the speed of the prime mover. It is achievable when variable speed drives are integrated into the systems. One example from the ABB Group shows how a variable speed drive is used by the production line hydraulic system of 90 bar. This hydraulic system inspects and retreats strip material. In this case, the variable speed drive is used to optimise the performance of the hydraulic positive displacement pump. This type of solution which includes variable speed drives could reduce the power consumption from 9 kW to 2 kW and improve the total energy efficiency within the system which results in 48% savings [27]. This type of an engineering solution is called the “low-energy pump system design” and the key component of it is the variable speed control drive providing the lowest energy consumption.

Variable speed drives regulate the speed and rotational force or torque output of the electrical motors. In hydraulic systems, pressure feedback is used as input information for the drive circuit. The power conversion circuit is based on voltage source inverter technology and high performance control strategy or direct torque control (DTC). DTC is a newly developed technology by the ABB Group and allows determination of a motor state at phenomenally high speed and reacts rapidly to sudden process and load changes [28].

Electromagnetic induction is the basis of AC motors control because the voltage in the stator windings forms the current and magnetic flux. The changes in magnetic flux contribute to the motors rotations. The control over this process is exercised by alterations in the frequency converter which changes the frequency and amplitude of the network voltage.

![Figure 5.6 Structure of the variable speed drive [28]](image)

The structure of variable speed drives is based on the voltage source inverter which is shown in Figure 5.6. As can be seen, an AC drive consists of a rectifier, DC circuit and an Inverter unit. The rectifier is used to convert a regular 50 Hz three-phase current into a DC current which filters and feeds into an inverter unit.
5.3 Flow rate studies within the initial pickling line hydraulic system

The task of sizing hydraulic accumulators for the initial part Pickling line hydraulic system can be accomplished if the flow rates within the hydraulic system would be studied. For that, the flow rates of each hydraulic cylinder and motor were calculated. The calculations of the flow rate, $Q_{CYL}$, for the hydraulic cylinders are based on equation 15.

$$Q_{CYL} = v \times A$$  \hspace{1cm} (15)

Where $v$ is the speed of the hydraulic cylinder in m/sec, $A$ is the correspondent side area. A conversion factor of $(60000/0.9)$ is used to get the flow rate data in [l/min].

As can be seen from equation 12, the flow from each side of the hydraulic cylinder would be different due to the differences in the effective working area.

Flow rate of the hydraulic motors $Q_{MOT}$ can be calculated by using equation 16:

$$Q_{MOT} = n \times D$$  \hspace{1cm} (16)

Where $n$ is the rotations per minute and $D$ is the hydraulic motor displacement.

For each hydraulic unit, the calculations of the flow rates were done in Matlab software and the resulting graph is in figure 5.7.

![The initial part Pickling line system Flow Rate vs Time, l/min](image1)

![The initial part Pickling line system Flow Rate histogram](image2)

**Figure 5.7 Calculated flow rate of the initial part pickling line hydraulic system vs. time and its histogram representation**

As can be seen from figure 5.7, the flow rates were integrated into one continuous representation which can describe the performance of the initial part pickling line hydraulic system during a single pickling line cycle. The maximum flow rate in the system is 623 l/min. The histogram representation of the calculated flow rate within the initial part pickling line hydraulic system shows that it does not follow the normal distribution pattern since most of the values are concentrated on the left side displaying a flow rate less then 100 l/min.
The flow rate data for each hydraulic unit are listed in table 4.5.

<table>
<thead>
<tr>
<th>Number</th>
<th>Hydraulic Unit</th>
<th>Flow Rate [L/min] Port A</th>
<th>Flow Rate [L/min] Port B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Press Roll Driving Motor</td>
<td>61.6667</td>
<td>61.6667</td>
</tr>
<tr>
<td>2</td>
<td>Press Roll Cylinder</td>
<td>214.4662</td>
<td>113.0973</td>
</tr>
<tr>
<td>3</td>
<td>Outboard Bearing Cylinder</td>
<td>139.0809</td>
<td>66.9814</td>
</tr>
<tr>
<td>4</td>
<td>Coil Diameter Measuring Cylinder</td>
<td>36.6519</td>
<td>17.6517</td>
</tr>
<tr>
<td>5</td>
<td>Double Coil Storage Motor</td>
<td>14.22</td>
<td>14.22</td>
</tr>
<tr>
<td>6</td>
<td>Uncoiler Mandrel Expansion Cylinder</td>
<td>179.0708</td>
<td>159.1740</td>
</tr>
<tr>
<td>7</td>
<td>Strip Center Guide Position Cylinder</td>
<td>15.708</td>
<td>15.708</td>
</tr>
<tr>
<td>8</td>
<td>Snubber Roll Adjustment Cylinder</td>
<td>104.7198</td>
<td>53.4071</td>
</tr>
<tr>
<td>9</td>
<td>Snubber Roll Drive Motor</td>
<td>42.22</td>
<td>42.22</td>
</tr>
<tr>
<td>10</td>
<td>Coil Break Roll Adjustment Double System Cylinder</td>
<td>112.901</td>
<td>54.3731</td>
</tr>
<tr>
<td>11</td>
<td>Coil Peeler Traverse Cylinder</td>
<td>104.7198</td>
<td>63.1565</td>
</tr>
<tr>
<td>12</td>
<td>Coil Peeler Double System Cylinder</td>
<td>47.1239</td>
<td>24.0332</td>
</tr>
<tr>
<td>13</td>
<td>Anti-coil Break Roll Cylinder</td>
<td>91.6298</td>
<td>55.2619</td>
</tr>
<tr>
<td>14</td>
<td>Pinch Unit Double System Cylinder</td>
<td>110.2699</td>
<td>69.0889</td>
</tr>
<tr>
<td>15</td>
<td>Top Roll Adjustment Double System Cylinder</td>
<td>110.2699</td>
<td>69.0889</td>
</tr>
<tr>
<td>16</td>
<td>Cutting Cylinder</td>
<td>386.0389</td>
<td>203.5752</td>
</tr>
<tr>
<td>17</td>
<td>Side Guides Double System Cylinder</td>
<td>607.3746</td>
<td>455.5309</td>
</tr>
<tr>
<td>18</td>
<td>Flattener Double System Cylinder</td>
<td>104.7198</td>
<td>78.5398</td>
</tr>
<tr>
<td>19</td>
<td>Strip Stabilizing Rolls Double System Cylinder</td>
<td>20.1062</td>
<td>10.2542</td>
</tr>
<tr>
<td>20</td>
<td>Top Roll Drive Motor</td>
<td>42.22</td>
<td>42.22</td>
</tr>
<tr>
<td>21</td>
<td>Top Roll Adjustment Cylinder</td>
<td>67.0206</td>
<td>34.1805</td>
</tr>
<tr>
<td>22</td>
<td>Sampling Device Double System Cylinder</td>
<td>13.09</td>
<td>6.3</td>
</tr>
<tr>
<td>23</td>
<td>Cutting DS-1 Cylinder</td>
<td>235.6194</td>
<td>150.7964</td>
</tr>
<tr>
<td>24</td>
<td>Cutting DS-2 Cylinder</td>
<td>16.7552</td>
<td>8.5451</td>
</tr>
<tr>
<td>25</td>
<td>Traverse Drive Cutting Tool DS-1 Cylinder</td>
<td>67.0206</td>
<td>34.1805</td>
</tr>
<tr>
<td>26</td>
<td>Traverse Drive Cutting Tool DS-2 Cylinder</td>
<td>67.0206</td>
<td>34.1805</td>
</tr>
<tr>
<td>27</td>
<td>Side Guides-2 Cylinder</td>
<td>41.5633</td>
<td>20.3575</td>
</tr>
</tbody>
</table>

5.3 Hydraulic accumulators sizing and simulations

The Accumulator Simulation Program (ASP) from HYDAC was used in this thesis work to simulate the initial part pickling line hydraulic system behaviour when piston type hydraulic accumulators were integrated into the hydraulic circuit of the line. ASP displays hydraulic processes
as a real gas simulation and therefore hydraulic accumulators can be sized accurately. ASP simulates the gas conditions in the accumulator taking into account the different types of accumulators such as piston, bladder, diaphragm and metal bellows and temperature ratios during operations. The ASP program can also simulate situations where more than one accumulator uses back-up nitrogen bottles. Based on the above simulations, the required accumulator volume for pulsation damping and pressure shock damping can be determined. The results of the simulation can be viewed as functions against time [29].

The input data for simulation in the AST software is the maximum and minimum working pressure, temperature ranges, flow directions, cycle data and cycle types. Cycle data is the complete information about flow rates in the hydraulic system for each millisecond within the full simulation time. The pressure range is from 140 to 160 bar, and the temperature range is from 20 to 45 °C.

The piston type hydraulic accumulator was chosen for the integration into the hydraulic line. The window containing main settings and flow rate data is shown in figure 5.8.

![Figure 5.8 Hydraulic accumulator pre-selection and flow-rate graph](image)

As can be seen from figure 5.8, the piston type hydraulic accumulator has a nominal volume of 50 litres and there are three units of a total volume of 150 litres which would be used at the same time. The nominal volume of back-up gas bottles is 50 litres and there are ten gas bottles with a volume of 500 litres.

The simulations were conducted when a hydraulic pump that delivers 100 l/min was used in the line. The results of the simulations are shown in figure 5.9.
Figure 5.9 Simulations results: pressure vs. time of accumulators and gas volume vs. time of back-up gas bottles

The simulation results which are shown in figure 5.10 can describe about the temperature behaviour and pressure against accumulator gas volume changes during the simulated pickling line cycle.

Figure 5.10 Temperature vs. time and pressure against accumulator gas volume

The simulation shows that there are fluctuations of temperature in the hydraulic line within acceptable limits. The system pressure changes towards 140 bar which is a predefined minimum system pressure. It then rapidly recovers to 160 bar.

The simulation could prove that the pressure in the hydraulic line is remaining at 160 bar throughout the whole pickling line cycle when only one pump with a rated capacity of 100 l/min was used along with three 50 litres hydraulic accumulators connected to 500 litres of back-up gas bottles.
6. Photovoltaic system design and simulation

6.1 Design objectives: pickling line as PV system load

When five powerful motors are running pumps to provide necessary power demand of an industrial hydraulic system, a false perception can be conceived that there is no place for a photovoltaic system in this situation. But as it was shown in the present work, just 3.3% of the energy is finding its way to become a useful output and run hydraulic actuators in the pickling line of the SSAB plant. A precisely calculated power demand of the pickling line can become an objective to conduct the study about how well a photovoltaic system can be fitted into the energy delivery chain of the SSAB steel plant.

As it was shown in this work, the pickling line system could be modified towards an energy efficient perspective so that the hydraulic accumulators could reduce the number of hydraulic pumps from five to one as it was shown in the simulation. As a result, only one electrical motor would be needed. For that kind of a solution, the grid-connected PV system should look like in figure 6.1. The PV system would make an attempt to supply energy to the AC electrical motor which in turn would run the hydraulic pump and convert energy into hydraulic form by charging hydraulic accumulators. Afterwards, hydraulic components of the pickling line would use this energy by making all required operations. It would be the first proposed PV system in this work when the power demand of the AC electrical motor (ASEA type, ABB) would be used as a PV system load.

The second proposed PV system would charge the hydraulic accumulators directly by using a DC brushless hydraulic pump, figure 6.2. In this case, the electrical load for the PV system coincides with the hydraulic components' energy demand when a DC hydraulic pump works periodically by charging hydraulic accumulators integrated into the pickling line.
The main difference between the two proposed PV systems is that in the first case, the AC motor must run continuously while in the second case, the DC brushless hydraulic pump would be only turned ON when the energy is consumed. In both solutions, the hydraulic accumulators would be used as energy storage components. During the time when there would not be need to run the DC brushless hydraulic pump the PV system can produce energy and supply it into the grid.

It is important to note that the design and simulation of photovoltaic systems for industrial purposes only became possible due to the integration of hydraulic accumulators into the pickling line hydraulic system. This is because these hydraulic accumulators were able to reduce short peaks of high power demand when the power demand would exceed 32 kW.

A photovoltaic system which would operate in Swedish or northern European climate conditions must be designed in an energy efficient manner because the cost of electricity for industries is still quite low. In this context, an inefficient PV system with a high cost of energy would not attract any interest in developing environmentally friendly solutions such as solar energy harvesting.

The SSAB steel plant is located in Borlänge which is in central Sweden. The climate in Borlänge is of humid continental type with large seasonal temperature variations. It has relatively warm and humid summers and sometimes severely cold winters with long spells of cloudy days. An important climate measure is the solar radiation distribution. In many ways, the solar radiation distribution is the driving force behind weather and climate [30]. The output of the photovoltaic system is strongly correlated to the incoming radiation.
6.2 Method and site studies

The main considerations of the method are to design a realistic photovoltaic system which would be able to cover a part of the energy demand of the industrial pickling line hydraulic system in the SSAB steel plant. It should also show that hydraulic accumulators integrated in the hydraulic line can store solar energy instead of the other energy storage components.

The design and PV system simulation is done in the PVSYST simulation program. The PVSYST software is a tool for developers of PV installations. It has a detailed data base of PV system components which can be simulated when they are in an interconnected form.

A PVSYST simulation of PV systems would help to determine what kind of energy yield a photovoltaic system of casual configuration can give. It can also help to deeply understand the solar resource at the site by examining the model of the incoming amount of solar irradiation. It would also help in understanding the energy storage capabilities of the hydraulic accumulators. Interpretation of the obtained results is the last step in the work.

There are three main objectives about the site studies which are boundary conditions in the PV system design:
- Geographical site location or meteorological conditions estimation
- Available area for the PV system installation
- Load estimation

Geographically, the PV installation would be located in Borlänge which has a latitude of 60.48 °N, longitude of 15.43 °E, and an altitude of 140 m. For simulation purposes, realistic weather conditions were generated in the Meteonorm software. PVSYST should be used for system analysis and simulation. Meteonorm is converting monthly average data into hourly values [31]. The climate data which is used for simulations consists of cases mostly considered to be of an average type of climate for a specific geographic region [32].

The waste roof of the building where the pickling lines of SSAB are located can be used for photovoltaic installations.

![Figure 6.4 The SSAB steel plant, roof of the pickling line building [33]](image)

The roof of the building has a length of 288 m, a width of 15 m and a slope of approximately 30° which makes 4320 m² available for use. It is covered with a special metal sheet of corrugated shape which can be seen in figure 6.4 and it faces south-west with the azimuth angle of -10°. There are no obstructions on the roof which can possibly shade the PV installation.
A typical grid-connected photovoltaic system should include the specifying of components as it is shown in figure 6.5. These components are:

- PV array
- Inverter
- Connections to Public Grid
- Connections to System Load
- Metering

A PV array is a combination of PV modules connected in parallel and in series. An inverter is an interfacing device between components with different characteristics because it is providing power conditioning operations. Metering is used to control the system outputs whereas connection boxes and fuses are special electrical equipment that is used to connect the inverter and power grid and to protect the load.
6.3 AC motor based pickling line photovoltaic system.

6.3.1 AC motor load description

The AC load based pickling line photovoltaic system would supply the energy demand of one AC motor which runs a variable hydraulic pump. This combination charges the hydraulic accumulators and delivers energy into the pickling line hydraulic system as shown in figure 6.1. The AC load profile is based on the electrical current measurements from five electrical motors which run the hydraulic system. The average power delivered from five motors is used to generate the load.

![Power delivered by AC type motor within one pickling line cycle](image)

Figure 6.6 Power delivered by AC type motor within one pickling line cycle

As can be seen in Figure 6.6, the maximum power is not exceeding 32 kW because it is assumed that hydraulic accumulators would be introduced into the pickling line.

Within the operations hydraulic system should take energy from the hydraulic accumulators when the power demand of the units would be high. The time when the hydraulic units would not work the running electrical motor would charge the hydraulic accumulators. Thus providing continuous energy storage in the pickling line.

The calculated total energy demand of the AC motor-pump combination is 6.395 kWh as it is shown in figure 6.7.
Figure 6.7 Calculated total energy delivered by AC type electrical motor

Now the energy use can be estimated by taking into consideration the fact that within one hour the pickling line is used three times and with a loss factor of 20%:

\[
\begin{align*}
E_{\text{HOUR}} &= 6.395kWh \times 3 \times 1.2 = 23.079kWh \\
E_{\text{DAY}} &= 23.079kWh \times 24 = 552.528kWh \\
E_{\text{MONTH}} &= 552.528kWh \times 30 = 16575.84kWh \\
E_{\text{YEAR}} &= 16575.84kWh \times 12 = 19891008kWh = 200\text{MWh}
\end{align*}
\]

Where \( E_{\text{HOUR}}, E_{\text{DAY}}, E_{\text{MONTH}} \) and \( E_{\text{YEAR}} \) are the energy demand per hour, day, month and year respectively.

The pickling line hydraulic system is running continuously 24 hours per day within the whole year but it cannot be left unattended and periodic maintenance work can sometimes take a few days. Calculations are made so the hydraulic system that runs 3 times per hour slightly oversizes the energy consumptions since the system can sometimes work twice per hour as well. The pickling line cycle duration is dependent on the thickness of the metal coil and can therefore vary by large margins.

6.3.2 Initial estimations of system sizing and component selection.

The roof area of SSAB which is one half of the building hosting pickling lines is 4320 m\(^2\) but for the system design, only 500 m\(^2\) which are visualized in figure 6.8 would be considered.
The next step in the design is the PV module selection. There are two leading technologies in PV module production which are the crystalline and thin film types. The mono-crystalline silicon Si has continuous crystal lattice structure having no defects or impurities. The process of production is quite complicated and it is called the Czochralski process.

The thin film photovoltaic solar cells are fabricated by the deposition of thin silicon films with a total thickness of 1 μm at low temperatures of around 200 degrees Celsius on different materials. Its advantage is that the technology is simple and faster to produce than the mono-crystalline solar cells. All PV systems are based on crystalline silicon technologies of thin-film having in common that certain number of solar cells connected in series to form a module.

The resulting energy yield from the technologies is not the same due to the intrinsic difference between them. The estimated efficiency of around 10% in general is higher for the mono-crystalline type but the latest thin film technology improvements show that this approach would give better results in terms of energy production and investment returns.

It is also known that the area which is required for different types of solar cells is listed in table 6.1.

<table>
<thead>
<tr>
<th>Monocrystalline</th>
<th>Polycrystalline</th>
<th>Thin Film</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-9 m²</td>
<td>7-10 m²</td>
<td>15-20 m²</td>
</tr>
</tbody>
</table>

The PV module REC 230 AE with the nominal power of 230 Wp manufactured by Renewable Energy Corporation (REC) is located in Sweden (Glava). It was chosen for the PV system installation and it belongs to the AE-series which combine a long lasting product quality with reliable power output and a predicted efficiency of 13.9% [34], figure 6.9. AE-series is a relatively new product because it appeared in the market in 2009.
The REC 230 AE photovoltaic module consists of multi-crystalline 156 x 156 mm cells covered with high-transparency glass with antireflection surface treatment. Its back sheet was assembled from a high performance polyester surrounded by an anodized aluminium frame. The main technical data was obtained from the PV modules specification and is listed in table 6.2.

<table>
<thead>
<tr>
<th>Technical Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Peak Power Watts $P_{\text{max}}$</td>
<td>230.1</td>
<td>W$_{p}$</td>
</tr>
<tr>
<td>2. Maximum Power Voltage $V_{\text{MPP}}$</td>
<td>29.4</td>
<td>V</td>
</tr>
<tr>
<td>3. Maximum Power Current $I_{\text{MPP}}$</td>
<td>7.8</td>
<td>A</td>
</tr>
<tr>
<td>4. Open Circuit Voltage $V_{\text{OC}}$</td>
<td>37.1</td>
<td>V</td>
</tr>
<tr>
<td>5. Shot Circuit Current $I_{\text{SH}}$</td>
<td>8.3</td>
<td>A</td>
</tr>
<tr>
<td>6. Temperature Coefficient of $P_{\text{MPP}}$</td>
<td>-0.46</td>
<td>%/°C</td>
</tr>
<tr>
<td>7. Temperature Coefficient of $V_{\text{OC}}$</td>
<td>-0.34</td>
<td>%/°C</td>
</tr>
<tr>
<td>8. Temperature Coefficient of $I_{\text{SH}}$</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>9. Module Efficiency</td>
<td>13.9</td>
<td>%</td>
</tr>
</tbody>
</table>

This choice of the PV module is based on the consideration that the manufacturer has the production line in Sweden which would simplify shopping, warranty, and maintenance questions. In the next year REC is transferring its production facilities to Singapore, nevertheless the company will continue to work in the European market.

Another factor is that this type of PV module has a proven record for other long term successful PV installations in many European countries such as Germany and Spain [36]. One more criteria is that fully detailed technical information of the REC 230AE photovoltaic module is integrated into the
PV system design simulation software PVSYST and is available for manipulations. Comprehensive technical data about the REC 230AE is found in appendix B.

According to table 6.1, 7 m$^2$ can be used as a basis for the manual calculations as a referred parameter for the required roof area of 1 kW$_p$ because the REC 230AE PV module is constructed from multi-crystalline type solar cells. If the roof is 500 m$^2$, the peak power can be found from equation 18:

\[
\text{Power}_{\text{peak}} = \frac{500\text{m}^2}{7\text{m}^2/\text{kW}_p} = 71.4\text{kW}_p
\]  

(18)

The peak power $P_{\text{max}}$ of 230.1 kW$_p$ for the REC 230AE is used to calculate the number of the required modules:

\[
\text{NumberPV}_{\text{module}} = \frac{71400\text{W}_p}{230\text{W}_p} = 311\text{st}
\]

(19)

The above calculations show that if SSAB would plan to install the PV system for every 500 m$^2$ of available roof area, 311 PV modules of 230 W$_p$ can be placed there and the total array peak power can be 71.4 kW$_p$. The investments should be based on this number. The roof area of half of the pickling line building is 4320 m$^2$ and it would provide the ability to install a system of 617 kW$_p$. This corresponds to 2683 PV modules possessing similar technical characteristics.

Seasonal variations affect PV modules’ energy production and during the design phase, it is important to estimate the voltage changes under different temperatures. The temperature coefficient of $V_{\text{OC}}$ means that the voltage would rise or drop when the ambient temperature changes each time by 0.34 V. The technical data is based on Standard Test Conditions which means that the temperature is 25°C, and if the temperature range for Borlänge is -10 to 60°C, the voltages would be:

\[
V_{\text{OC}}(at -10^\circ\text{C}) = 37.1\text{V} + 35(0.34\text{V}) = 49\text{V}
\]

\[
V_{\text{MPPT}}(at -10^\circ\text{C}) = 29.4\text{V} + 35(0.34\text{V}) = 41.3\text{V}
\]

\[
V_{\text{MPPT}}(at +60^\circ\text{C}) = 29.4\text{V} - 35(0.34\text{V}) = 17.5\text{V}
\]

(20)

As can be seen from the voltage calculations, the PV modules have better performance when the temperature is low as compared to high temperature conditions. The modules yield 49 V for low temperature and 17.5 V for high temperature respectively. PVSYST calculates the voltage ranges and matches them with inverter technical characteristics automatically.

The next intrinsic component of the photovoltaic system is the grid-tie inverter. The size of the inverter power must be kept below the PV array peak power by 5 to 10 % [12], but the voltage and maximum input current of the inverter must be kept higher than the PV array voltage and current under worse conditions. The inverter should support the reliable and safety grid connection operation of the PV system. It should generate high quality power to the AC system. Thus the inverter is the most important part of the PV system because if it is not selected properly, losses of energy would occur.
The inverter of 20 kW power, Sunsys 24K-A, of the French Industrial Group ‘Socomec’ was thus chosen. The voltage range of the inverter is from 200V to 1000V and its maximum efficiency is 98.1%. The inverter is on the European market from 2009. The ‘Socomec’ Industrial Group is specialising in power supply, control and security in the industrial sector [37]. The main technical data of the inverter, Sunsys 24K-A, is listed in table 6.3.

**Table 6.3 Inverter Sunsys 24K-A technical parameters are listed in the table**

<table>
<thead>
<tr>
<th>Technical Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Minimum MPP Voltage</td>
<td>200</td>
<td>V</td>
</tr>
<tr>
<td>2. Min. Voltage for PNom</td>
<td>350</td>
<td>V</td>
</tr>
<tr>
<td>3. Nominal MPP Voltage</td>
<td>660</td>
<td>V</td>
</tr>
<tr>
<td>4. Maximum MPP Voltage</td>
<td>1000</td>
<td>V</td>
</tr>
<tr>
<td>5. Absolute max. PV Voltage</td>
<td>1000</td>
<td>V</td>
</tr>
<tr>
<td>6. Power Threshold</td>
<td>100</td>
<td>V</td>
</tr>
<tr>
<td>7. Nominal PV Power</td>
<td>20.5</td>
<td>kW</td>
</tr>
<tr>
<td>8. Maximum PV Current</td>
<td>60</td>
<td>A</td>
</tr>
</tbody>
</table>

The technical data about Sunsys 24K-A inverter is integrated into PVSYST, appendix C.

The Sunsys 24K-A inverter is designed to operate in Europe because it supports 50 Hz of output frequency and a voltage of 230-240 volt which make it ready to be connected directly to the power grid.

**6.3.3 Photovoltaic system design and simulation in PVSYST program.**

The PVSYST sizing started from the desired area of the SSAB roof which is 390 m², figure 6.4. The simulation shows that it was necessary to decrease the PV system size because the system worked inefficiently supplying more power to the grid than to the load. During the simulations the optimal size of 290 m² which can encompass 176 REC 230AE PV modules with a nominal power of 40.5 kW was chosen to be documented. This corresponds to the use of two Sunsys 24K-A inverters of nominal AC power of 40 kW when the nominal PV DC power is 35.9 kW, figure 6.10.
As can be seen from figure 6.10, the simulated PV system has 8 strings of 22 modules connected in series. The sizing which was done automatically is in figure 6.11.

The number of PV modules which can be connected in series must be in relation to the inverter voltage characteristics. For this PV system, the inverter can allow 23 PV modules to be connected in series. The number 22 was chosen because the total voltage of the system in this case would be 549 V, and the maximum load voltage is 525 V. This match would simplify electrical connections within the system. A total of eight strings gave a high value of the system current of 66.4 A. The
current which is now present in the pickling line is about 70 A. The high current would require special wirings. The array power distribution is directly proportional to the system voltage and it holds information about the PV system performance. The power curve must be as smooth as possible because strong fluctuations can lead to significant system losses. Factors such as the temperature of solar cells, available solar irradiance, and component efficiencies alter the system output.

The PV system simulation is based on the meteorological data generated in the Meteonorn software for Borlänge, Sweden and integrated into the PVSYST data base. The orientation of the system coincides with the building position and in PVSYST, the azimuth angel was set to -10 and PV panels were tilted by 45°, figure 6.12.

![Figure 6.12 Settings in the PVSYST, azimuth and tilt](image)

The users’ energy consumption is 552.528 kWh per day, and they are used to form the monthly energy demand as shown in PVSYST, figure 6.13.

![Figure 6.13 PV system users needs](image)
The simulation shows that the total system production is 37 MWh per year whereas the user needs are 202 MWh. The system loss diagram is reflecting the energy flows during the simulation, figure 6.14.

As can be seen from figure 6.14, under Standard Test Conditions, an energy of 1097 kWh/m$^2$ was receive by the PV array which amounted to 318130 kWh of available energy. Out of this total amount, only 44418 kWh was converted by a conversion efficiency of 13.9%.

Array losses and inverter losses reduce energy available at the inverter output to 37477 kWh and as a result, 35701 kWh of energy is supplied to the user and 1777 kWh is fed to the grid. It means that 95.3% of energy which was produced by the PV system is delivered to the user and 4.7% of the energy is supplied to the grid. Totally the system could deliver 17.6% of the energy needed by the user. The main simulation results are summarized in table 6.4. Appendix D contains other simulation results of the PV system.

Table 6.4 Results of the PV system simulation are listed in the table

<table>
<thead>
<tr>
<th>System Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. System Production</td>
<td>37477</td>
<td>kWh/year</td>
</tr>
<tr>
<td>2. Normalized system production</td>
<td>2.54</td>
<td>kWh/kWp/day</td>
</tr>
<tr>
<td>3. Specific production</td>
<td>926</td>
<td>kWh/kWp/year</td>
</tr>
<tr>
<td>4. Performance ratio</td>
<td>0.817</td>
<td></td>
</tr>
<tr>
<td>5. Reference incident energy</td>
<td>1132.69</td>
<td>kWh/m$^2$/year</td>
</tr>
<tr>
<td>6. Array losses</td>
<td>0.49</td>
<td>kWh/kWp/day</td>
</tr>
<tr>
<td>7. System losses</td>
<td>0.07</td>
<td>kWh/kWp/day</td>
</tr>
</tbody>
</table>
The reference incident energy is the relation of total irradiance on the PV array to the reference irradiance which is 1000 W/m² accordingly to STC. This parameter estimates how well the PV system was placed, tilted, and oriented as it is giving estimation of the available solar resource.

The normalized system production is equal to 2.54 kWh/kW_p per day. The parameter indicates the energy balance within the PV system because it is the relation between the total energy yield per year and the available energy at the inverter output. It is also used to compare systems of different sizes because it is not related to the system scale, figure 6.15.

![Figure 6.15 Normalized PV system production](image)

The relation between two parameters described above is the performance ratio. The performance ratio is the free parameter from the PV system size and location because it is the result of the division of normalized production by reference incident energy. Moreover, it only stresses on the PV system abilities to produce energy. The performance ratio is 81.7% which indicates that only 18.3% of the energy was lost due to conversion losses and efficiencies of the system components including wires. Performance ratios for each month are in figure 6.16.

![Figure 6.16 PV system performance ratio](image)
Comparison of the energy need of the user, energy which was supplied to the user, energy that was injected into the grid, and the corresponding solar fraction are given in figure 6.17.

Figure 6.17 Comparison of the needs of the user with the energy supplied to the user and the energy injected into the grid on the right and solar fraction on the left side

The solar fraction is fluctuating throughout the year from 5% in winter months to 32% in the summer period. Solar fraction is the relation of energy supplied to the user and energy consumed by the user and it is reflecting renewable energy gain in the energy consumption profile of the consumer.

6.4 DC brushless hydraulic pump based pickling line photovoltaic system

6.4.1 DC brushless hydraulic pump load description

The DC brushless hydraulic pump based pickling line photovoltaic system would supply the energy demand of one DC brushless hydraulic pump which would charge the hydraulic accumulators as shown in figure 6.2. In this case, the load energy consumptions are the same as the hydraulic line energy consumptions.

On the right side of figure 6.18, the hydraulic line power consumptions can reach 90 kW at their maximum. On the left side is the case when hydraulic accumulators would be integrated into the hydraulic line, the peaks over 40 kW would be eliminated and energy demand would be spread evenly over the whole working cycle of the pickling line system in the SSAB steel plant.
Figure 6.18 Hydraulic line power consumptions without and with integrated hydraulic accumulators

The total energy, which was consumed by the hydraulic line within a single pickling line working cycle is 1.0575 kWh as it was calculated in chapter 5. Figure 6.19 reflects hydraulic line energy consumptions of hydraulic components in each second within a single pickling line cycle.

Figure 6.19 Energy consumptions of the pickling line spread over one pickling line cycle

Energy demand of the planned PV system can be estimated in a similar way as it is in chapter 6.3.1.

\[
E_{\text{hour}} = 1.0575 \text{kWh} \times 3 \times 1.2 = 3.806 \text{kWh}
\]

\[
E_{\text{day}} = 3.806 \text{kWh} \times 24 = 91.320 \text{kWh}
\]

\[
E_{\text{month}} = 91.320 \text{kWh} \times 30 = 2739.6 \text{kWh}
\]

\[
E_{\text{year}} = 2739.6 \text{kWh} \times 12 = 32875.2 \text{kWh} = 33 \text{MWh}
\]  

The calculations show that total energy demand per year is 33 MWh.
6.4.1 Photovoltaic system design and simulation in PVSYST program.

For the PV system which would supply the demand of DC brushless hydraulic pump, the same system components such as the REC 230AE PV module and the Sunsys 24K_A inverter would be used which can potentially simplify the comparison between two PV systems.

During the simulations the area of 109 m² showed the best results because the PV system supplied reasonable amount of energy to the grid but spent more to feed the demand of the load. If the area was bigger more energy were supplied to the grid than to run the motors.

The roof area of 109 m² of the SSAB pickling line building would be used for the PV modules installations. The area can hold 66 REC 230AE PV modules with a nominal PV power of 15.2 kW_p. One inverter Sunsys 24K-A would be used in the system, figure 6.20.

<table>
<thead>
<tr>
<th>Number of modules</th>
<th>Nominal PV Power</th>
<th>15.2 kW_p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Module area</td>
<td>Maximum PV Power</td>
<td>13.5 kW_dc</td>
</tr>
<tr>
<td>Nb. of inverters</td>
<td>Nominal AC Power</td>
<td>20.0 kW_ac</td>
</tr>
</tbody>
</table>

![Global system summary](image)

**Design the array**

- **Number of modules and strings**
  - Mod. in series: 22
  - Nbre strings: 3
  - Overload loss: 0.0%
  - Pfrom ratio: 0.76

<table>
<thead>
<tr>
<th>Operating conditions</th>
<th>Vmpp (60°C)</th>
<th>549 V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vmpp (20°C)</td>
<td>677 V</td>
</tr>
<tr>
<td></td>
<td>Voc (-10°C)</td>
<td>924 V</td>
</tr>
<tr>
<td>Plane irradiance</td>
<td>1000 W/m²</td>
<td></td>
</tr>
<tr>
<td>Impp (STC)</td>
<td>23.1 A</td>
<td>Max. operating power: 13.4 kW</td>
</tr>
<tr>
<td>Ioc (STC)</td>
<td>25.4 A</td>
<td>at 1000 W/m² and 50°C</td>
</tr>
<tr>
<td>Ioc (at STC)</td>
<td>24.9 A</td>
<td>Array nom. Power (STC): 15.2 kW_p</td>
</tr>
</tbody>
</table>

**Figure 6.20 Global PV system summary and PV array design**

As can be seen from figure 6.20, the simulated PV system has 8 strings of 22 modules in series. The PV system nominal power is 15.2 kW_p. The sizing which was performed in PVSYST is given in figure 6.21.
As can be seen from figure 6.21, the system voltage is 549 V and the current is 24.9 A. The current in the system is relatively low which would simplify the usage of the wiring and controlling equipment.

In the same way as it was in the previous system, the simulation in PVSYST would be based upon the meteorological data generated in the Meteonorm software. The orientation and tilt of the PV system would remain at -10° and 45° correspondingly.

The PV system load energy demand of 2760 kWh was generated in PVSYST based on the monthly values from equations. The users profile generated by PVSYST is in figure 6.22.
The simulation shows that the total system production is 14 MWh per year whereas the user needs are 33 MWh. The system loss diagram is reflecting the energy flows during the simulation, figure 6.22.

Figure 6.22 PV system Loss diagram

The PV system Loss diagram indicates that the system can produce 13999 kWh of energy from a total energy of 119573 kWh which is received by the PV array. However, the PV modules have an efficiency of 13.9% and losses of the PV array and the inverter are 13.2% and 3.2% respectively.

A total of 8795 kWh of energy or 62.8% of the total system production were supplied to the load while 5204 kWh or 37.2% were supplied to the grid. The PV system could thus deliver 26.7% of the energy necessary to run the DC brushless hydraulic pump. The PV system simulation results are in table 6.5 and in appendix D.

Table 6.5 Results of the PV system simulation are listed in the table

<table>
<thead>
<tr>
<th>System Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. System Production</td>
<td>13999</td>
<td>kWh/year</td>
</tr>
<tr>
<td>2. Normalized system production</td>
<td>2.52</td>
<td>kWh/kWp/day</td>
</tr>
<tr>
<td>3. Specific production</td>
<td>921</td>
<td>kWh/kWp/year</td>
</tr>
<tr>
<td>4. Performance ratio</td>
<td>0.813</td>
<td></td>
</tr>
<tr>
<td>5. Reference incident energy</td>
<td>1132.69</td>
<td>kWh/m²/year</td>
</tr>
<tr>
<td>6. Array losses</td>
<td>0.5</td>
<td>kWh/kWp/day</td>
</tr>
<tr>
<td>7. System losses</td>
<td>0.08</td>
<td>kWh/kWp/day</td>
</tr>
</tbody>
</table>

The reference incident energy is 1133 kWh/m²/day. Normalized system production is equal to 2.52 kWh/kWp per day, figure 6.23.
The performance ratio is 81.7% which indicates that only 18.3% of the energy was lost due to conversion losses and efficiencies of the system components including wires. Monthly values of the performance are in figure 6.24.

Comparison of the energy need of the user, energy which was supplied to the user, energy injected into the grid, and the corresponding solar fraction are given in figure 6.25.
Figure 6.25 Comparison of the needs of the user with the energy supplied to the user and the energy injected into the grid on the right and solar fraction on the left side

The solar fraction is fluctuating throughout the year from 10% in winter months to 74% in the summer period.

6.5 Photovoltaic systems comparison and conclusions

The main idea of the PV system comparison is to understand the scale and behavior of the PV system loads. The loads are not identical but they must supply the demand of the same pickling line hydraulic system. Different solutions for powering the hydraulic system led to different amounts of power consumptions. Two grid-connected PV systems were simulated in PVSYST on an hourly base. The results gave a better understanding of the system performance over a period of time because they were summarized in tables and graphs.

In the first case when the load was an AC type motor which was in turn running the hydraulic pump, the PV system used 290 m$^2$ of available roof area under the pickling lines in the SSAB steel plant. The second time it was enough to use 109 m$^2$ to get a decent photovoltaic system solution. The nominal power of the first system is 40 kW$\text{p}$ and the second is 15.2 kW$\text{p}$, the reference incident energy on the PV array plan is the same for both systems as it depends on the system location and orientation. The normalized system production ratio and performance ratio are 2.54 and 0.817 for the 40 kW$\text{p}$ system and 2.52 and 0.813 for the 15.2 kW$\text{p}$ PV system respectively. These two parameters are almost the same because they both indicate that the design of the PV systems is quite optimal.

Linear dependence of the generated power on the irradiation level is a leading quality of PV energy generation and the rate of PV production can be estimated as the value of the slope of these curves. Daily input/output diagrams of both PV systems, figure 6.26 show that power generation has stable linear fashion and PV array efficiency is not really strongly dependent on the incoming irradiation, but other factors such as the temperature dependence can affect the performance more.
Totally the system of 40 kW<sub>p</sub> produces 37477 kWh of energy and the system of 15.2 kW<sub>p</sub> produces 13999 kWh of energy. The first system is covering 17.6% of the total load energy demand, and the second is covering 26.7% of the load energy demand.

The main idea which is behind this solar system design is the presence of the hydraulic accumulators in the pickling line hydraulic system. The behaviour of hydraulic accumulators was modelled in the HYDAC accumulator simulation software. It showed that the power demand of the pickling line could be corrected so that high power peaks would be blurred away by the compensation flows from the hydraulic accumulators when hydraulic components would be actively consuming power.

As a result these two PV systems show that the part of the energy which is needed to run the system was stored in the hydraulic accumulators and the PV system was continuously providing power to the load due to its smooth power consumption profile.

Further experiments could be done with simulations to show how well the hydraulic accumulators can store energy that originates from the sun.

7. Conclusions

- This thesis work showed that the PV system can supply a significant part of the energy demand of the industrial system such as the initial part of the pickling line hydraulic system at the SSAB steel plant.

- Hydraulic accumulators can work as solar energy storage quite effectively.

- A way was found to generate a realistic load sequence for the simulation of the PV system through precise energy consumption calculations within the hydraulic line.
The energy efficiency analysis could show that the initial part pickling line hydraulic system works with a low efficiency of 3.3%.

The reasons that reduced energy efficiency with the SSAB pickling line were discovered and analyzed. The main reason is that the system is oversized because it was designed for the worst case upset conditions and because of this, there was always an excess flow in the system. Due to this, the pickling line continuously operated in throttling mode due to partially closed valves which wasted a lot of energy.

It was concluded that the hydraulic system at SSAB needed modernization because it works with very low energy efficiency.

It was shown that the modernization of the pickling line can occur in two ways. The first way is modernization in an incremental manner and the second way is through major changes.

Incremental changes can be done by introducing hydraulic accumulators into the existing hydraulic system. It was shown that it would improve total system performance and hydraulic accumulators could be used as energy storage devices. Hydraulic accumulators would also help in doing system resizing. It was also shown that variable speed drives integrated into the energy supply chain would reduce energy requirements of the hydraulic system.

It was shown that major changes such as equipment replacement will help to improve the energy efficiency within the hydraulic system drastically. For this, modern high efficiency motors and coordinate control valves should be used for a new redesigned system.

It showed that the PV system could become a solid part of the energy supply chain contributing towards a sustainable production future for the SSAB group.
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9. Appendices

Appendix A

Current measurements and correspondent power of the hydraulic motors P1, P2, P3, P4 and P6:
Appendix B

Comprehensive technical data about REC 230 AE PV module taking from PVSYST simulation software.
Appendix C.

Comprehensive technical data about Sunsys 24K-A inverter taking from PVSYST simulation software.
### Appendix D

Simulations result of the PV system with 40 kWp in PVSYST program.

#### Balances and main results

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