HEAT TREATMENT ENERGY MAPPING

MSc in Resource Recovery
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Abstract

As the world becomes more focused on sustainability, there is increasing pressure on steel-bearing companies to improve their energy efficiency and reduce their carbon footprint. The heat treatment process accounts for about 25% of SKF's energy consumption, and it aims to achieve decarbonized operations by 2030 and the supply chain by 2050. Therefore, improving the energy efficiency of the heat treatment process can have significant economic and environmental benefits for the company.

This thesis project aimed to conduct an energy mapping of different heat treatment processes at SKF to develop a methodology and standard key performance indicator for establishing energy performance and ensuring comparability between installations and processes. Three heat treatment processes were studied: through hardening, location A; case carburizing, location B; and surface induction hardening, location C.

A detailed methodology and guidelines for carrying out energy mapping were developed. A standard key performance indicator known as Specific Energy consumption in kWh/kg at a particular utilization in % was set for comparisons among different heat treatment processes. Regression analysis was used to normalize the results.

On the same utilization level, case carburizing, location B consumes more energy than through hardening, location A. Surface induction hardening, location C consumes 90% less than others and is less dependent on utilization. The carbon intensity in g CO2-eq/kg for greenhouse gas scopes 1, 2 and 3 were also studied. Case carburizing, location B had the highest climate impact due to the coal-based electricity mix of the country. Hence, the future availability of renewable electricity is critical when switching from gas to electricity across factories in SKF.

Note: The exact values of all results and all the graphs' Y-axis in this work were redacted for confidentiality.

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1. Introduction

Climate change threatens all life on earth, and human activity has been accelerating this threat. To save our planet, the Paris Agreement's goal of keeping the rise in global temperatures to 2° C above the pre-industrial age and mitigating climate change effects must be achieved. Greenhouse gas emissions must be reduced drastically to achieve a climate-neutral world by mid-century. However, achieving this goal has been difficult due to the constant energy demand rise in the world due to the ever-growing human population, increased production of consumer goods, and rising use of energy-intensive devices. The current energy crisis in Europe due to the Ukraine-Russia war has worsened this situation, and there is an urgent need to find solutions immediately.

The steel-bearing industry significantly contributes to the global manufacturing sector, providing essential components for various industrial applications from the automotive to aerospace industries. However, this industry is also one of the most energy-intensive, consuming significant energy to produce high-quality steel bearings. Specific data on the energy consumption of the steel-bearing industry is not readily available, as it is often grouped with other segments of the steel industry. According to the International Energy Agency (IEA, 2020), the steel industry consumes around 6-7% of the world's total energy consumption and is responsible for about 7-9% of global greenhouse gas emissions. As the world becomes more focused on sustainability, there is increasing pressure on steel-bearing companies to improve their energy efficiency and reduce their carbon footprint.

AB SKF is a leading global manufacturer of premium steel bearings, and they have recognized the need to reduce their energy consumption to improve sustainability. They aim to achieve decarbonized operations by 2030 and the supply chain by 2050 compared to a 2019 baseline, with an estimated CO_{2}-eq total emissions of 2 million tonnes. The targets cover scope 1 and 2 emissions, scope 3 upstream emissions, and scope 3 downstream emissions resulting from SKF-controlled logistics. (AB SKF, 2022). The heat treatment process is a critical part of their production process. It involves heating and cooling steel to achieve specific properties and characteristics and improve metal components' mechanical properties and durability. Heat treatment currently accounts for about 25% of SKF's energy consumption. Therefore, improving the energy efficiency of the heat treatment process can have significant economic and environmental benefits for the company.

Previous studies have been carried out by JST consultancy to find out how much energy is needed for heat treatment. However, they only focused on the furnace's energy consumption and compared the energy consumption per kg of different furnace types. They did not include the consumption during furnace evacuation, holding time, hardening, quenching, or oil bath. The results show that carburizing consumes the highest with 2.54 kWh/kg, followed by vacuum hardening at 1.93 KWh/kg, and the lowest is direct hardening under a protective atmosphere at 1.01 kWh/kg. (Jiří Stanislav, 2022). Bodycote Värmebehandling AB conducted an energy audit on one of its heat treatment plants at Angered and represented its results in 3 Key performance indicators (KPIs): energy use/production time of 1.16 MWh/hr, energy use/turnover of 0.18 MWh/kSek and energy use/amount of goods of 2.93 MWh/ton. (Kallen, 2012). A steel mill in Singapore also conducted an energy audit on its plant, representing its result in specific energy consumption of 1,095 kWh/t rolled steel. (Ho, Chou, & Chandratilleke, 1991). The Indian Bureau of energy efficiency (Energy Performance Assessment of Furnaces, 2022) also stated its key performance indicator for energy performance assessment of furnaces as specific energy consumption.

Previous Internal studies have also been done at SKF. One was a master's thesis titled *Energy Management in heat treatment* by Pontus Berg. He worked on the E-factory heat treatment process for bainitic hardening and got results of 3.5 kWh/kg and 15,618,762 kWh/yr. (Berg, 2014). Davis & Nilsson (Comparing Energy Use and Environmental Impact of Induction Hardening and Through Hardening, 2012) also compared the energy use and environmental impact of induction hardening and through hardening and found that induction hardening has 40% less primary energy demand than through hardening.

This thesis project aims to conduct an energy mapping of different heat treatment processes at SKF to develop a methodology and standard key performance indicator for identifying energy performance and ensuring comparison. The research will conduct theoretical studies on boundary specifications, data collection, measurements, key performance indicators, methodology, energy balance calculations, and energy efficiency analysis in different heat treatment processes. The findings of this research will provide a detailed methodology and guidelines for carrying out heat treatment energy mapping. It will also provide valuable insights into the energy use and efficiency of the various heat treatment processes in the steel-bearing industry and contribute to developing sustainable and efficient practices. The results will also be used to suggest improvements to the existing process and as input for future investment decisions at SKF.

1.1. Scope & Boundary

This project focuses on mapping the energy requirements of the heat treatment process of the steel-bearing manufacturing process only. It takes account of all significant energy-consuming equipment necessary for the heat treatment process to be carried out and their auxiliary equipment. It doesn't consider processes not directly required for the heat treatment process, like transportation of materials, building heating, controls, and lighting. The scope covers all processes between forming and machining for each heat treatment process (figure 1). All energy-consuming inputs into the system, like electricity, natural gas, methanol, and nitrogen, will be considered.

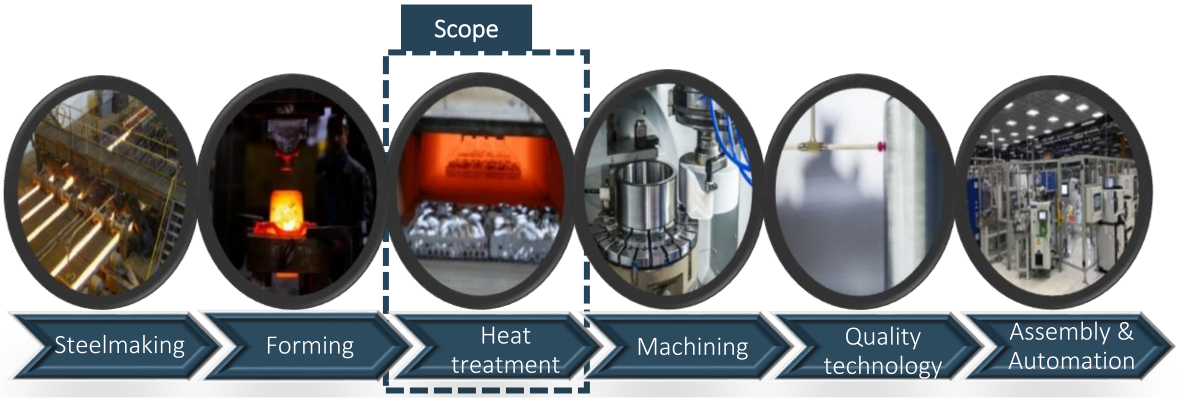

Figure 1: Scope of heat treatment energy mapping

The five significant processes included in this heat treatment energy mapping include the washing systems, the heating systems, the atmosphere systems, the quenching systems, the cooling systems, and the drying systems (Figure 2). All other non-essential systems, like transportation of materials, lighting, building heating, and controls, are excluded from this analysis. This is a general scope as not all heat treatment types contain all these five systems separately; induction hardening, for example, might not have a washing system for some factories and has a single system that does both quenching and cooling. The process flow and systems covered in each heat treatment process will be examined in detail while presenting their respective results later.

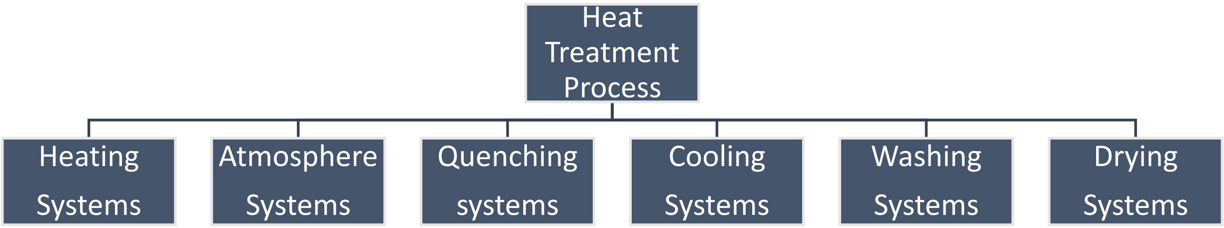

Figure 2: Key processes of the heat treatment energy mapping

1.2. Objectives

The main objectives of this project can be described by the following research questions:

1. What standard KPI can be used to compare different heat treatment processes?
2. How can it be measured, calculated, or represented?
3. What should this calculation or measurement consider, and what can be neglected?
4. How much energy is being consumed for the total heat treatment process?
5. Which of the heat treatment plants studied has better energy performance?
6. Which systems in each heat treatment process are more significant in energy use?
7. What measures can be taken to improve the energy efficiency of the processes?
8. What additional energy measurement points can be implemented to help continuously monitor the energy consumption of the heat treatment process?

2. Heat Treatment Process

Bearing components are heat treated to provide the right mechanical (strength & toughness) or physical (thermal stability) properties required for the given application/process. Bearings are mainly made of steel, a mixture of iron and other alloying atoms such as carbon, chromium, nickel, molybdenum, silicon, or manganese. These alloying atoms are present in different proportions depending on the grade of the steel. Carbon is the most important alloying element to obtain sufficient hardness/strength. When the carbon content in the iron is less than 2%, it is known as steel, but when it is above 2%, it is known as cast iron.

The microstructure of iron can exist in different phases or structures depending on the arrangement of its atoms. Ferrite, austenite, cementite, martensite, pearlite, bainite, and troostite are examples of these different microstructures, and they all have different mechanical and physical properties. SKF's desired microstructure for its bearings is martensite or bainite, and to achieve this, the material has to be heated up and cooled under specific conditions (Figure 2). These specific conditions give rise to different heat treatment processes. The heat treatment processes are divided into two main categories: through hardening and surface hardening. Through hardening, either bainitic or martensitic results in homogenous microstructures and properties through the whole cross-section of the component. Surface hardening, either by induction hardening or thermochemical hardening like carburizing, carbonitriding, low-pressure carburizing/carbonitriding, or solution nitriding, results in a hardness profile from the surface to the core (Swerea IVF, 2012).

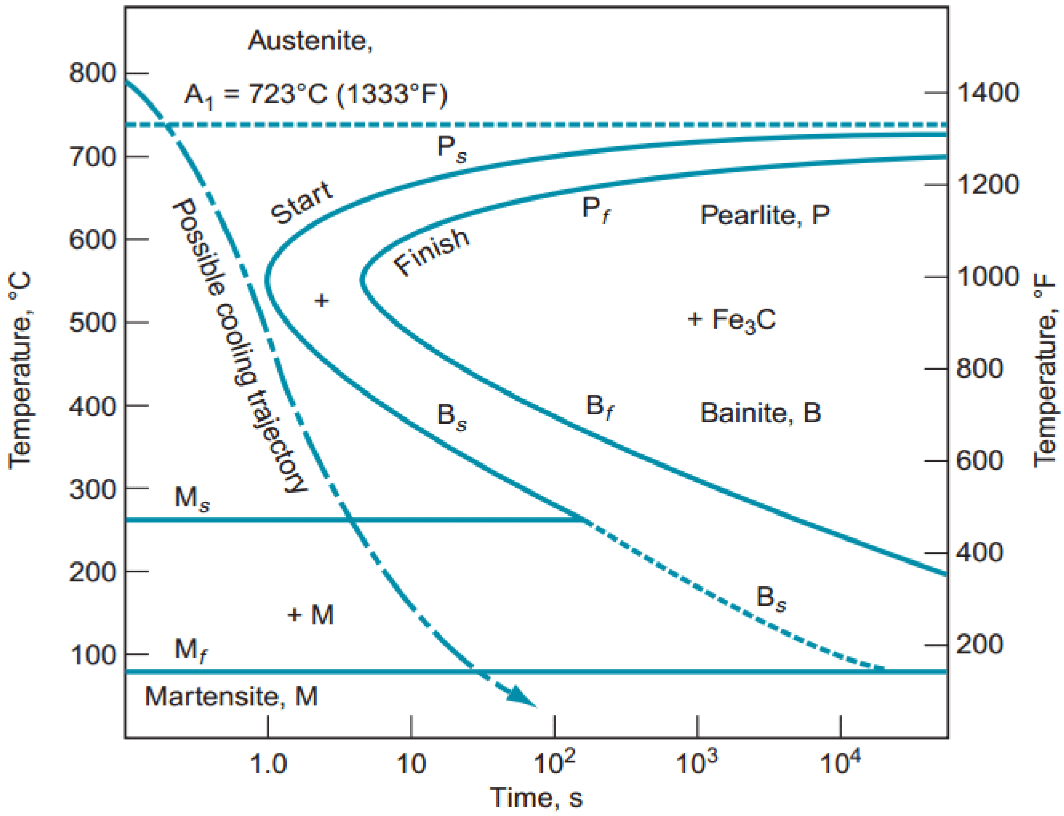

Figure 3: The Time-Temperature Transformation curve, showing the transformation of austenite into other phases as a function of time and temperature for a composition of 0.80% C steel (Molla, 2018)

2.1. Through Hardening

Hardening, as the name implies, involves heating the entire cross-section of the steel component from surface to core. It results in homogenous microstructures and properties throughout the whole cross-section of the component (AB SKF, 2022). It has two main types, namely bainitic hardening and martensitic hardening.

2.1.1. Bainitic through hardening

Bainitic hardening involves heating the steel component to high austenitization temperatures of about 840 - 880°C using a natural gas or electric-fired furnace (figure 4). The difference between this and martensite is in the quenching process. Here, it is quenched in molten salt baths to temperatures above martensitic temperature (200-300°C) and held at this temperature in transformation baths of molten salt for 3-7 hrs depending on material grade and size. The treatment is ready when >99% of the austenite has transformed into bainite. No tempering is required after this process as the material is not as hard as martensitic hardening and hence somewhat tougher (Swerea IVF, 2012).

2.1.2. Martensitic through hardening

Martensitic hardening involves heating the steel component to high temperatures of about 840 - 880°C to achieve austenitic microstructures using a natural gas or electric-fired furnace (figure 5). It is then quenched rapidly to a low temperature of about 150°C, typically in oil or molten salt. After quenching, most of the austenite is transformed to martensite, but some are still not transformed, remaining as retained austenite. The temperature is lowered further to achieve more transformation with post-quenching in a water bath below 10°C. Martensitic transformation results in a volume increase of about 0.3% after the hardening. The martensite formed is hard but also brittle, so it needs to be tempered in a furnace or molten salt bath to give it sufficient toughness to be used in applications and prevent cracking (Swerea IVF, 2012).

Figure 4: Bainitic Hardening (AB SKF, 2023)

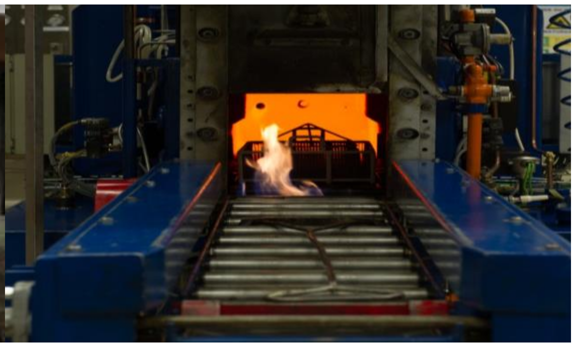

Figure 5: Martensitic hardening (AB SKF, 2023)

2.2. Induction Hardening

Induction hardening is a surface hardening process where the heat source for heating the steel component to high austenitization temperatures is not done by a furnace but an induction coil (figure 6). It works based on the principle of electromagnetic induction, which is the process of inducing an electric current in a conductive material by exposing it to a changing magnetic field. When a high-frequency alternating current flows through a coil made of copper profile, it generates a rapidly changing magnetic field around the coil. When a conductive material, such as metal, is placed within this changing magnetic field, eddy currents are induced in the material. These eddy currents create heat within the material, causing it to heat up. (HVH Industrial Solutions, 2023). After heating, it is quenched rapidly by showering a mixture of water and polymer. This process takes seconds to minutes and is very fast compared to the through-hardening process, which takes hours. Since only the surface is heated, it is expected to consume less energy and have better environmental impacts. This process usually leads to martensitic microstructure; hence, tempering is required afterwards (Swerea IVF, 2012)

2.3. Thermochemical Hardening

These are processes by which carbon or nitrogen atoms are diffused into the steel components' surface to improve their properties. There are three main types of thermochemical hardening depending on the atom diffused into the steel component: case carburizing, carbonitriding, and nitriding/nitrocarburizing.

2.3.1. Case Carburizing

Case carburizing involves carbon diffusion into the steel component's surface in a furnace (figure 7) at 900-1000°C, followed by quenching in a salt bath. It then goes through a secondary re-hardening process followed by quenching and tempering. This results in a carbon gradient from surface to core. The high carbon content at the surface gives a high hardness, and the low carbon content at the core gives a high toughness. It also causes compressive residual stresses in case-hardened material, making it suitable for harsh conditions such as poor lubrication, shock loads, or elevated temperatures. (AB SKF, 2022).

2.3.2. Carbonitriding

Carbonitriding follows the same process as case carburizing, except carbon and nitrogen are diffused into the steel component's surface. It results in a robust surface microstructure with higher hardness, carbide and nitride precipitates, tailored retained austenite, and compressive residual stresses. It is also applied in harsh conditions like off-highway, mining, and steel mills. (AB SKF, 2022)

2.3.3. Nitriding/ Nitrocarburizing

Nitriding/Nitrocarburizing is also surface enrichment by nitrogen or nitrogen and carbon, resulting in a very hard surface layer with improved wear and corrosion resistance.

2.3.4. Low-pressure Carburizing/Carbonitriding

Low-pressure carburizing/carbonitriding is a novel technology that involves using a low-pressure or vacuum furnace for the heating process instead of the atmospheric furnace (figure 8). It can reach temperatures above 1000°C and has been said to be a green technology for sustainable cost reduction. This is because it has reduced process time compared to case carburizing and carbonitriding. The natural gas utilization here is also optimized, as there is no atmospheric air exchange since the system operates under a vacuum. The products are also cleaner than the other processes since the quenching here is done with nitrogen gas and not molten salt; hence, the washing tanks are unnecessary. It also consumes less energy and, therefore, has less environmental impact. (AB SKF, 2022)

Figure 6: Induction hardening

Figure 7: Case Carburizing (AB SKF, 2022)

Figure 8: Low pressure carburizing (AB SKF, 2022)

3. Methodology of Energy Mapping

The International Organization for Standardization ISO 50001 (ISO 50001 Energy management, 2018) requires organizations to establish a systematic approach to energy management, and energy mapping is an integral part of this approach. By identifying energy savings opportunities through energy mapping, organizations can reduce their energy consumption, lower costs, and improve their environmental performance. ISO 50001 is a standard that provides guidelines for establishing, implementing, maintaining, and improving an organization's energy management system (EnMS). One of the key requirements of an EnMS is to perform an energy review, which includes energy mapping.

Energy mapping is a process of identifying and analyzing the energy flows in a system or region. It is a crucial step towards developing effective energy management strategies and promoting sustainable energy use. Here are the steps involved in the methodology for energy mapping:

i. **Scope and boundaries**: The first step in energy mapping is to clearly define the scope and boundaries of the study. This includes identifying the system or region to be studied, the types of energy sources and uses to be considered, and the time period for the analysis. This definition is a continuous process as it should constantly be revisited after different stages of the energy mapping to make adjustments based on data availability and the results' significance.

ii. **Inclusions and exclusions**: The next step is to decide which systems on the process flow will be measured based on their quantitative significance. Theoretical calculations, assumptions, and rules of thumb can be used to estimate which systems are more significant to measure and which ones can be excluded or represented by a factor or coefficient.

iii. **Process flow identification**: Identify and map out the heat treatment process flow, including the energy inputs and outputs and the energy losses of all energy-consuming equipment, such as furnaces, quenching, and cooling systems. This can be done using flow diagrams, block diagrams, or other process mapping techniques.

iv. **Energy consumption measurement:** Measure the energy consumption of each piece of equipment in the heat treatment process using energy meters, such as power meters, gas meters, or flow meters. This can be done by installing energy meters, data loggers, or other monitoring devices.

v. **Data collection and analysis:** Collect data on the energy consumption of the heat treatment process, including the types of fuels used, the energy consumption rates, and the operating parameters of the process. This data can be obtained from energy meters, control systems, and other monitoring devices. The data collected from the energy consumption measurement should be analyzed to determine the energy consumption patterns and trends. This can help determine the current energy performance of the process and show the improvement potential.

vi. **Energy Balance:** Conduct an energy balance to determine each part of the process's energy inputs, outputs, and losses. The energy balance should account for all energy inputs, including fuel consumption, electrical energy consumption, and heat losses.

vii. **Energy consumption characterization:** Characterize the energy consumption by determining the energy consumption per production unit, specific energy consumption, energy intensity, or other KPIs. The analysis would also be done considering the KPIs based on the utilization of the process and the load carriers. This will make the KPIs comparable to other factories and processes.

viii. **Energy Efficiency Analysis**: Potential optimization areas can be identified and analyzed based on the energy consumption characterization. This may include comparing the energy consumption of different heat treatment processes, identifying energy losses that can be reduced, implementing energy-saving technologies, improving the process flow, or modifying equipment to improve energy efficiency.

ix. **Continuous monitoring and reporting:** Energy mapping should be a continuous process, with regular monitoring and reporting of energy consumption and the results of any optimization efforts. This can help ensure that energy consumption remains optimal and that improvements are sustainable over time. Suggest what should be measured or enhancements to the current measuring system to ensure continuous monitoring and reporting. This would serve as input to subsequent projects carried out by the metering and monitoring team regarding implementation.

It is essential to involve relevant stakeholders in the energy mapping process, such as process engineers, energy managers, and maintenance personnel, to ensure that all aspects of the heat treatment process are considered and to promote a culture of energy efficiency within the company. These steps can create a comprehensive energy map of the heat treatment process, and opportunities for reducing energy consumption can be identified and evaluated. By regularly conducting energy mapping and implementing energy-saving measures, SKF can reduce its energy consumption, improve its energy efficiency, lower energy costs, and improve its overall sustainability.

3.1. Defining Key Performance Indicators (KPIs)

The following are some key performance indicators (KPIs) that can be used to measure and compare the energy consumption of heat treatment processes in the steel-bearing industry:

i. **Energy consumption per unit of production:** This measures the amount of energy consumed per unit of steel-bearing produced and helps compare the energy efficiency of different heat treatment processes. It is calculated by dividing the total energy consumed by the total bearings produced.

ii. **Specific energy consumption**: This measures the energy consumption per unit of mass of steel-bearing processed, and it helps compare the energy efficiency of different heat treatment processes for a given steel grade. It is calculated by dividing the total energy consumed by the total weight of steel processed.

iii. **Energy intensity:** This measures the amount of energy required per unit of time and helps compare the energy efficiency of different heat treatment processes under various operating conditions.

iv. **Energy recovery rate**: This measures the proportion of energy that is recovered and reused during the heat treatment process and helps identify areas for improvement in energy efficiency.

v. **Energy cost per unit of production**: This measures the cost of energy consumption per unit of steel-bearing produced, and it helps evaluate the financial impact of energy consumption on the overall profitability of the process. It is calculated by dividing the total energy cost by the total bearings produced.

vi. **Energy consumption per unit of process parameter**: This measures the energy consumption per unit of a specific process parameter, such as temperature, duration, or cooling rate, and it helps identify areas for improvement in energy efficiency.

vii. **Carbon Intensity**: Carbon intensity measures the carbon emissions associated with energy consumption during heat treatment. It can be used as a KPI to assess the environmental impact and carbon footprint of the energy used.

It is important to note that these KPIs should be combined and evaluated in the context of the specific heat treatment process and the type of steel produced to provide an accurate picture of the energy consumption performance. Other factors, such as utilization and production loads, must be considered when comparing different heat treatment technologies. By regularly tracking these KPIs, steel companies can identify areas for improvement in their heat treatment processes and reduce their energy consumption and emissions.

4. Results and Discussion

This study was carried out on three different heat treatment processes: through hardening, induction hardening, and thermochemical hardening. Hence, the results would be reported and discussed individually for each, and finally, a comparative analysis of all three processes would be done.

4.1. Through Hardening (Bainitic/Martensitic, Location A)

The factory in location A is mainly used for bainitic hardening but can also be used for martensitic hardening. It has two lines, namely A and B. Each line was designed for a specific maximum operating capacity, but the normal operating capacity is 40% lower than the maximum operating capacity. A mix of products is hardened in this furnace, including spherical roller-bearing rings greater than 400 mm inner diameter, spherical roller thrust-bearing rings of all sizes and some rollers. The scope and process flow chart of this process is shown below in Figure 9.

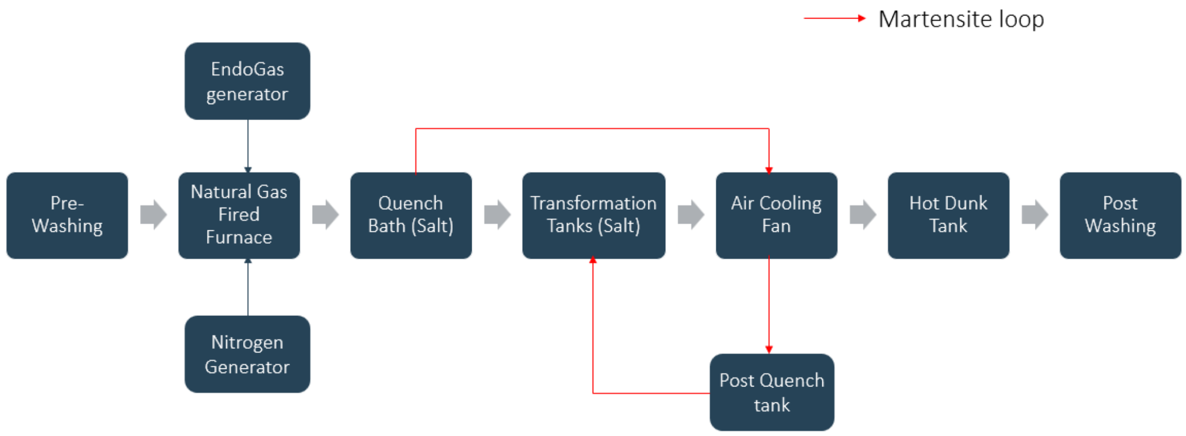

Figure 9: Through Hardening (Bainitic/Martensitic) process flow

The bainitic hardening process follows the ash arrows in Figure 9 directly to the end. The material is first washed to remove any dirt from it, as this will affect the heating process in the furnace. The pre-wash tank has a built-in drying section with hot air to remove any moisture after washing, as moisture on the steel material will negatively affect the furnace atmosphere and cause decarburization. Moisture on the metal parts will also cause drying marks on the surface of the products. After washing, heating in the furnace is carried out.

The furnace is a recuperative natural+bio gas-fired furnace that operates under atmospheric pressure. It has a risk of decarburization due to air inflow from the environment affecting the furnace atmosphere. Decarburization is carbon loss at the surface of the steel material due to lower carbon content and activity in the furnace atmosphere. This will result in lower hardness of the steel material and is avoided by injecting gases into the furnace to serve as a protective and slightly active atmosphere. This protective atmosphere will also prevent air or oxygen from entering the furnace, avoiding oxidation or scaling. A mix of endogas and nitrogen is used in the furnace as the protective atmosphere. This contains CO, CO_2, H_2, N_2, and CH_4. The endogas is produced from the incomplete combustion of natural gas using the endogas generator with nickel catalyst.

After heating, the products were quenched rapidly in molten salt and then held in two-stage transformation tanks of molten salt for hours. It is then taken out and air-cooled with fans before being placed in the hot dunk tank to wash off some salt. The final process is the post-wash machine, where spray nozzles on both sides spray water and detergent in the first section to wash the material in the first compartment. Then the second compartment has clean water sprays, and the last compartment has air knife nozzles that spray hot air to dry the material.

The martensitic hardening follows the same process as the bainitic hardening except for adding an extra loop between the quench tank and the transformation tank, as shown by the red line in Figure 9. Also, the quench bath temperature for martensitic transformation is lower, so a temperature reset is usually done in the quench bath during martensitic production. After the quench tank, the material goes to the fans for air-cooling and then to the post-quench tank to increase the degree of martensitic transformation. After the post-quench tank, it goes to the transformation tank for tempering and continues the bainitic hardening loop.

4.1.1. Production Data

To get the specific energy consumption, the production data and utilization of the factory have to be looked at. The production data from the supervisory control and data acquisition (SCADA) system were collected for 2022. The data was made available by the energy manager for location A.

This production data obtained from the SCADA system records what has gone through the heat treatment process. But it doesn't consider what gets to the machining department after heat treatment. The system's applications and products in data processing (SAP) record the products made available to the machining department. The data shows a 9% reduction from the data from the SCADA system. This is because, after heat treatment, some products go to scrap or return to the heat treatment process for rehardening if they don't meet the quality or product specifications for machining. There can also be time lags between when the product finishes heat treatment and when it goes for machining. This difference is relevant in looking at the value-added KPIs.

The utilization values were calculated based on the current product mix's maximum operating capacity and maximum calendar hours. The maximum design capacity was not used because the product mix has changed due to changed business demand over the years. The equation for calculating the utilization is shown below:

$$\frac{Weight\ of\ material\ produced\ per\ month}{maximun\ operating\ capacity\ per\ hour * hours\ per\ day * days\ per\ month} *\ 100\%$$

$$\frac{X\ kg/month}{X\frac{kg}{hr} * 24\frac{hrs}{day} * X\frac{days}{month}} *\ 100\%$$

The utilization value has been low due to changes in product mix and volumes. The utilization value was also calculated based on the scheduled production hours. The scheduled production hours are calculated by taking out the days of no production from the calendar hours, which accounts for holidays, maintenance, lack of demand, or any other unaccounted downtime. Using the SAP production data, the utilization drops by 2%. Figure 10 shows the variation in utilization across the different months.

The utilization values for lines A and B were reasonably stable from January to June, but in July, they went down drastically because of a lack of production due to maintenance. After maintenance, both lines were started up in August, but line B was shut down in September and October, and all production was done with line A. This decision was taken to conserve energy as production demand was low.

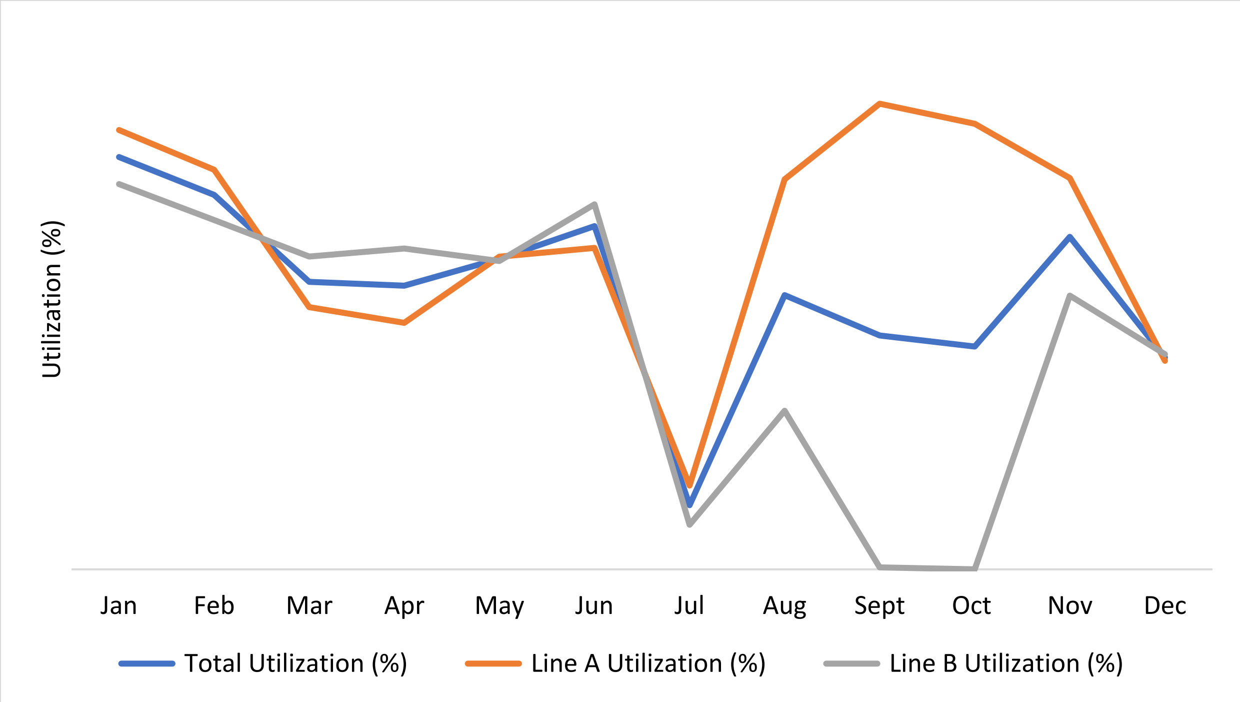

Figure 10: Graph showing utilization for the location A factory

4.1.2. Energy Data

The energy consumption data for location A is obtained from the installed energy meters, which transfer the data to the Grafana system, where the data is logged and stored. The data was made available by the energy manager for location A. Not all equipment in the location A factory has separate meters logging its energy consumption. Still, the factory has a main meter that logs the electricity consumption of the entire location A factory. So, adding up the energy readings of the equipment with meters and subtracting them from the main location A energy meter readings gives the energy consumption of the remaining unmeasured equipment. This is why the pre-wash tank, post-wash tank, hot dunk tank, post-quench tank and air-cooling fan have their values together. The energy data for each piece of equipment includes all auxiliary equipment attached.

The natural gas consumption is logged by flow meters for the whole factory, which supplies the location A factory and another nearby factory. There is no separate meter logging the natural gas consumption of the location A factory; hence mass allocation was used in this analysis to split the whole natural gas consumption across both factories. This might affect the sensitivity of the results of this analysis as one cannot tell if both factories use endogas purely based on their production masses, which is an input for future studies. These natural gas values include the natural gas for the furnace burners and the natural gas input to the endogas generator to produce endogas. But there were days when there was no production in both factories, and there were still natural gas consumption readings on those days. Assigning the natural gas consumption on those days to either factory becomes challenging; however, the total unaccounted natural gas consumption for days of no production in 2022 accounts for 4.9% of both factories' natural gas consumption. If half of it is added to the natural gas consumption of location A factory, it would increase location A natural gas consumption by

3% and increase the total energy consumption of location A factory by 1%. Hence it is negligible. The natural gas consumption values in m^3 were converted to energy values in kWh by using the relationship that 1 Nm^3 equals 10 kWh. (Kašpárek, 2023)

Nitrogen is generated on-site by a nitrogen generation unit operated by Air Liquide Company. The unit supplies nitrogen to all plants within the location A factory area. But, the amount of nitrogen produced on-site is not enough to meet the nitrogen requirements of all plants, so some nitrogen is bought through trucks and added to the tanker as supplements. The on-site nitrogen generation unit produces 76% of the total nitrogen demand, and the rest is bought. The Location A factory accounts for 50% of all nitrogen consumption and takes up 66% of the nitrogen produced on-site.

4.1.3. Theoretical Heat Energy Demand

This is achieved by carrying out an energy balance around each piece of equipment in the system using the energy conservation law. The law of energy conservation, also known as the first law of thermodynamics, is a fundamental principle of physics that states that energy cannot be created or destroyed, only transformed from one form to another. In other words, a closed system's total energy remains constant over time. This law is based on the principle of conservation of mass and energy, which suggests that the sum of total mass and energy in a system is constant. This study is focused on thermal energy as this is a heat treatment process. The thermodynamic equation for heat transfer is given as follows.

$$Q = m\, c_p\, \Delta T$$

Where Q = amount of heat transferred (gained or lost) by the material in joules (j)
m = mass of material in kilograms (kg)
C_P = specific heat capacity of the material in j/kg/°C
ΔT= change in temperature in °C

This equation was used to calculate the energy required for heating up (heat gained) or cooling down (heat lost) the steel-bearing material at each stage of the heat treatment process. The total energy required for all stages of the bainitic hardening heat treatment process under ideal conditions was obtained as 0.24 kWh/kg, while that of the martensitic hardening process was obtained as 0.29 kWh/kg. The average value for the through-hardening process was 0.26 kWh/kg. The difference between this value and the measured value shows how much energy is lost in the process and possible energy-saving potentials. It gives a theoretical benchmark for our energy-saving implementations.

4.1.4. Key Performance Indicators (KPIs)

Choosing a KPI for the through-hardening process was decided, considering the process runs with different product mixes simultaneously at any point in the furnace. So, using a product-based KPI would be impossible as one cannot split the energy data across the various product mixes due to the different recipes and specifications. A theoretical energy demand calculation was done on the process, and the results show that the process's energy consumption largely depends on the masses of the products rather than their individual properties. Also, the recipes indicating the time and temperatures the product batches spend in each step process largely depend on the mass. Hence, using a time-based KPI, such as Total Energy (kWh/yr), and a mass-based KPI, such as Specific energy consumption (kWh/kg), becomes the best possible solution for representing the results of this analysis. It also ensures that the results can be compared to other heat treatment processes with the same KPI. The equation for calculating the specific energy consumption is shown below:

$$\frac{Total\ energy\ consumed\ per\ month\ in\ kWh}{Total\ weight\ produced\ per\ month\ in\ kg}$$

The KPI results cover the product and the carrier weight. If the carrier weight is removed, the KPI values drop by 4.3%.

Figure 11 shows the way the energy consumption of each piece of equipment is split across different energy sources and their relative percentages. Natural gas accounts for 34% of the total energy consumption, while electricity accounts for 66%. The results show that the significant energy consumers of this process are the furnace, quench, and transformation tanks, accounting for 80% of the total energy consumption.

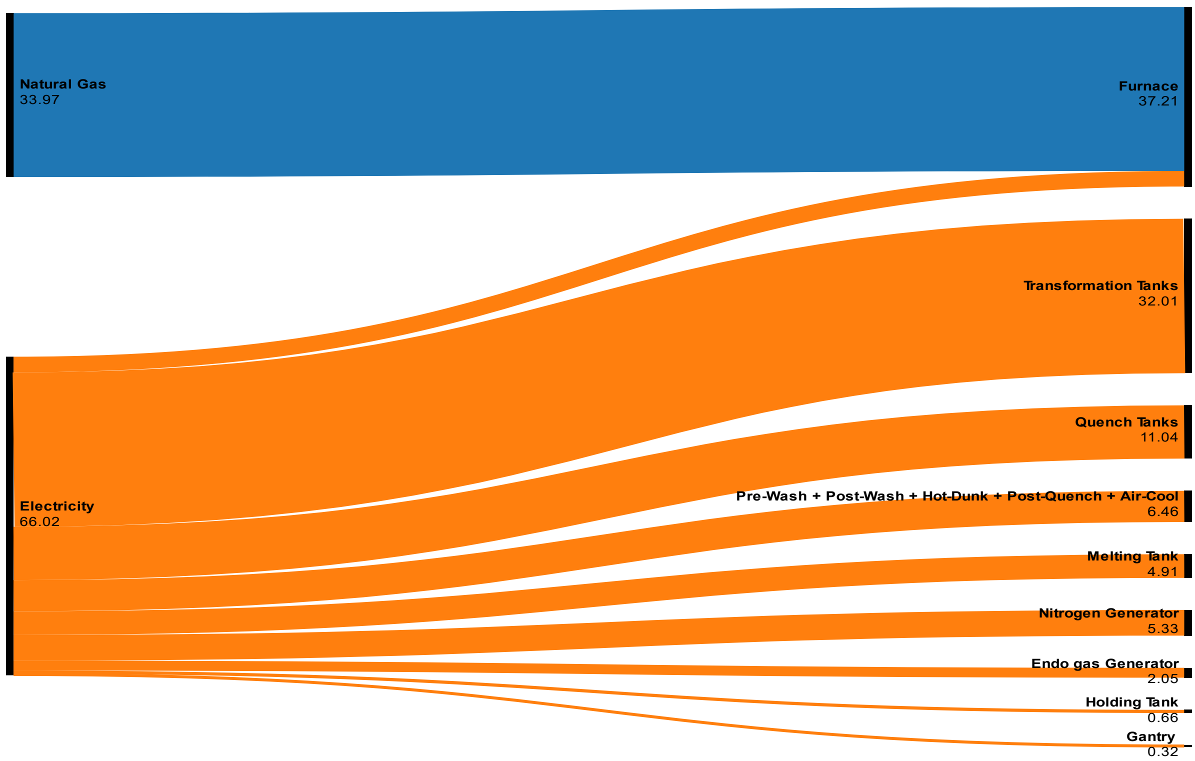

Figure 11: Sankey diagram showing the % distribution of energy consumption across equipment.

The specific energy consumption changes for each piece of equipment with respect to changes in production weight for each month were studied. This shows which equipment is following the production well regarding energy performance so that energy improvements would be focused on those that aren't. The gantry's values are stable and seem to run a constant energy consumption irrespective of the production volume. The furnace, quench, and transformation tank show the highest variability in values and show that the energy consumption does not follow the production pattern. Hence, this equipment has many energy losses, and energy improvement efforts should be focused on here.

Figure 12 above shows the variation in the specific monthly energy consumption; a trend is seen across the months except for July, which had eight days of production due to maintenance.

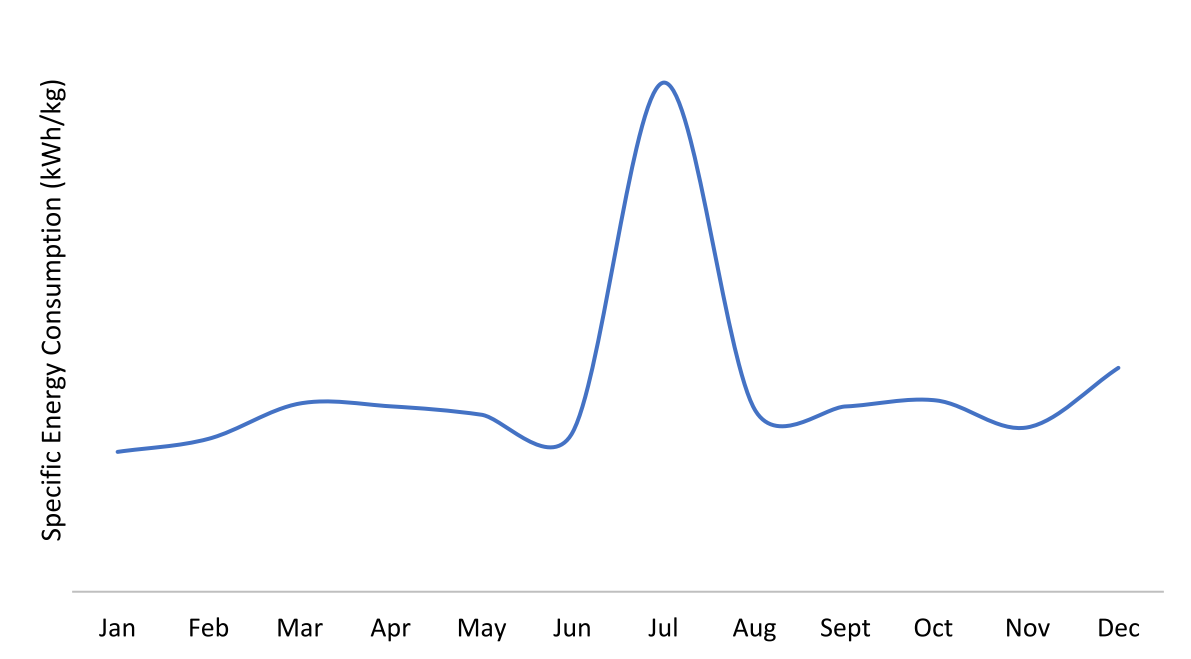

Figure 12: Specific Energy consumption for the different months in 2022 (Through hardening).

4.1.5. Regression Modelling

Location A factory operates at a certain utilization based on the current product mix's operating capacity. To make the KPI values in this analysis comparable to other heat treatment processes, one must use values showing the same utilization range for the different processes, as utilization affects a plant's energy consumption. The results show that the utilization has an inverse relationship with the specific energy consumption. As the utilization increases, the specific energy consumption reduces, and vice versa.

Higher utilization can drastically reduce the specific energy consumption of the plant. Hence a regression analysis (figure 13) was carried out to predict the specific energy consumption at different utilization rates of location A factory. Four regression models, namely linear, power, exponential, and polynomial, were used to try to fit the data, and the power regression model fits the data best. An equation that related utilization to specific energy consumption was obtained. It was used to predict the specific energy consumption at 100% utilization of the normal operating capacity of the plant. Hence, 53% of the current energy consumption can be reduced if the factory is utilized better.

The equation relating Specific Energy Consumption to Utilization:

$$y = A\,x^{-b}$$

Where y = Specific Energy consumption in kWh/kg

And, x = Utilization in %
A and b are constants

The R-squared value of 0.8468 and the randomness of the residual plot of the predicted Y-values shows a good fit between the power regression model and the measured data.

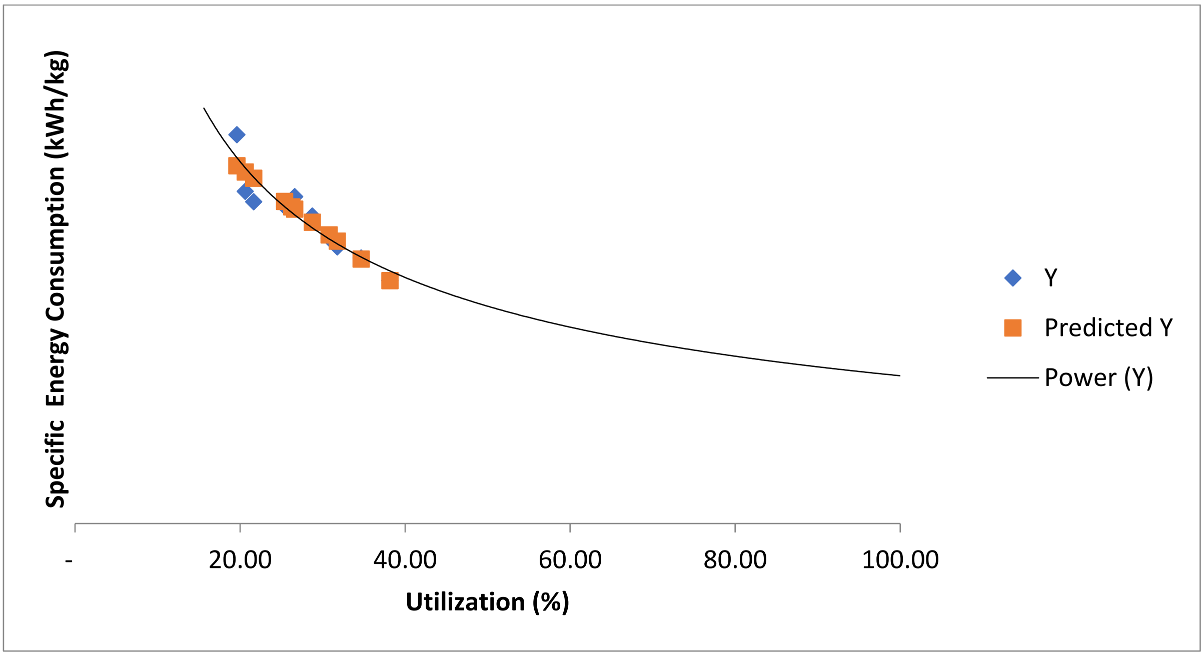

Figure 13: Regression plot of specific energy consumption against utilization for through hardening.

4.1.6. Installed Capacity Rule of Thumb for Energy Consumption

Installing energy meters on every piece of equipment is not financially feasible. Therefore, having a rule of thumb that relates the energy consumption rate to the installed capacity will be beneficial to the continuous study and monitoring of the system. This will give approximate estimations for systems where measuring devices cannot be installed immediately. This analysis was carried out on the location A factory.

The results show an average of about 30% across the board for the energy consumption rate based on the installed capacity. This is not an absolute value but can give suggestive guidelines for approximate estimations when equipment does not have an energy meter installed. It can also help guide or predict energy analysis results.

4.1.7. Environmental Impact

The source of the electricity used at location A is hydropower from Vattenfall AB. The environmental product declaration document for purchases between 2019 and 2023 released by Vattenfall AB (Summary of EPD® of Electricity from Vattenfall's Nordic Hydropower, 2021) shows that their electricity's global warming potential or greenhouse gas emissions are 7.26 g CO_2-eq/kWh_{el} for scope 3 emissions. The natural gas consumed is sourced as biogas-certified RedCert with a greenhouse gas emission of about 45 g CO_2-eq/kWh for scope 3 emissions. Scope 1 and 2 emissions for hydropower electricity and biogas are low and negligible. The equation for calculating the carbon intensity is shown below:

$$Carbon\ Intensity = Emmision\ coefficient * specific\ energy\ consumption$$

These values can be used to estimate the environmental impact of the energy consumption of through hardening heat treatment process in terms of greenhouse gas emissions.

Figure 14 shows that despite natural gas contributing only 34% of energy consumption, it accounts for 76% of the emissions. This is an opportunity to improve natural gas sources and replace the natural gas-fired burners with electrically heated burners sourced from hydropower.

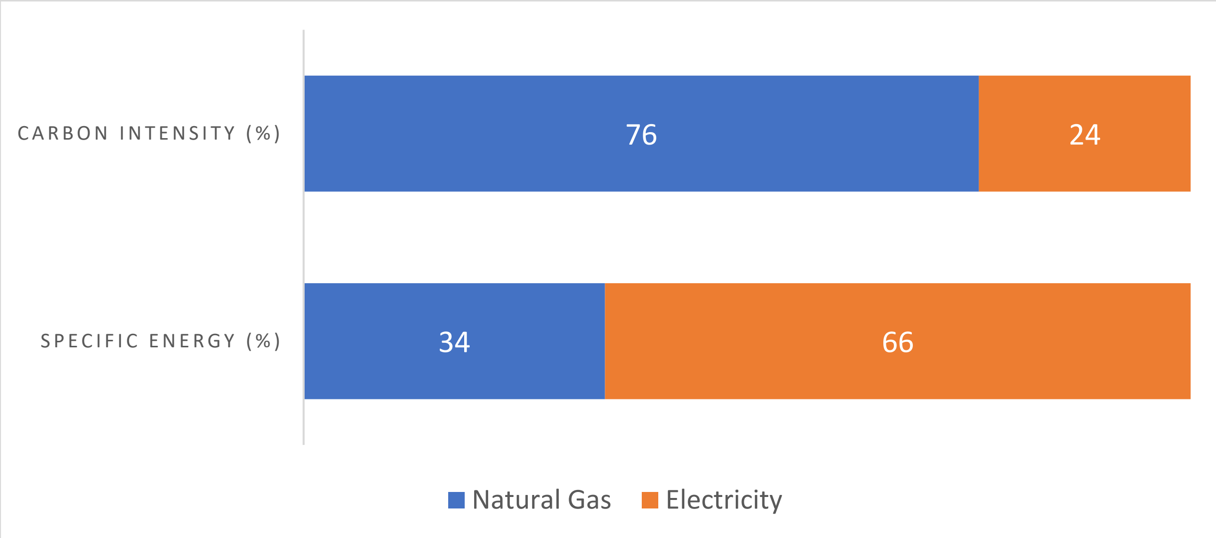

Figure 14: Environmental impacts of Through hardening process.

4.1.8. Summary of results

The results show that 91% of the current energy consumption is energy loss to the environment from the process, and 4% is lost to the carrier weight. 53% of energy consumption can be reduced by optimizing utilization, and 38% of energy consumption can be reduced theoretically by implementing energy savings and efficiency.

4.1.9. Energy Metering

Energy meters cannot be installed at every point due to financial constraints. Some points are critical and need to be measured, while others are either not critical or can be calculated from other metered points. Table 1 below shows the list of possible metering points for location A through hardening process with explanations of their level of priority or criticality.

Table 1: Energy metering for the Through hardening process.-

Equipment	Currently Measured	Comments
Central Meter (Electricity)	Yes	This central meter measures the total electricity consumption of all equipment connected to the heat treatment process. This is very important as it helps

		to have a holistic idea of the electricity consumption of the entire process. It also helps in auditing each piece of equipment's electricity consumption to be sure the values they show add up to the central meter value. It can also help estimate the electricity consumption of equipment that doesn't have meters attached to them by subtracting the sum of the other equipment from the central meter value.
Central Meter (Natural gas)	No	This central meter measures the total natural gas consumption of all equipment connected to the heat treatment process. This is very important as it helps to have a holistic idea of the natural gas consumption of the entire process. It also helps in auditing each piece of equipment's natural gas consumption to be sure the values they show add up to the central meter value. It can also help estimate the natural gas consumption of equipment that doesn't have meters attached to them by subtracting the sum of the other equipment from the central meter value.
Furnace (Electricity)	Yes	The furnace is the most critical equipment of the process as it carries out the primary heating process and consumes the most energy. For a natural gas-fired furnace, this electricity measurement is for all auxiliary equipment like drives, roof fans, exhaust fans, and combustion fans connected to the furnace. This meter would include the heater and the auxiliary equipment for an electrically heated furnace.
Furnace (Natural Gas)	No	The natural gas used for the burners should be measured for a natural gas-fired furnace. Also, if any natural gas is added as part of the protective atmosphere, that should be measured too. This is essential to see the natural gas consumption rate for studies on the impact of using natural gas-fired burners or electric heaters.
Transformation Tanks (Electricity)	Yes	This is the second-highest energy consumer that consumes a lot in keeping the salts molten. The tanks are also open, so they have lots of heat loss. The energy meter should include electric heater

		banks and other attached auxiliary equipment like agitators.
Quench Tanks (Electricity)	Yes	The Quench tanks consume considerable energy because of the heat loss of molten salt and open tank. The energy meter should include all auxiliary equipment like heaters, agitators, drives, elevators, dampers, fans, and rollers attached to the tank.
Melting Tank (Electricity)	Yes	This is used to melt fresh salt to refill the quench and transformation tanks when the levels go down, and it always has some salt on standby. This meter measures the heater's energy consumption and all attached auxiliary equipment.
Endogas Generator (Natural Gas)	No	This is a high consumer of natural gas, and it is essential to know how much natural gas is for the natural gas-fired burners and how much is for endo gas production.
Endogas Generator (Electricity)	Yes	This is not a top consumer. But it is relevant to see the difference between implementing different endo gas generation configurations and sources.
Pre-wash Tank (Electricity/Natural Gas)	No	The pre-wash tank is natural gas-fired for one factory but electrically heated for others. Depending on the configuration of the particular factory, the electricity or natural gas consumption should be measured.
Hot dunk Tank (Electricity)	No	This is used to wash some salt off the material after the transformation tank, not to saturate the post-wash tank. It might be consuming considerable energy and needs to be evaluated.
Air-cool Fan (Electricity)	No	This is an air-cooling fan for material at high temperatures. It might be consuming considerable energy and should be evaluated.
Post quench Tank (Electricity)	No	This chiller system cools the material from high temperatures to low temperatures. It might be consuming considerable energy and should be evaluated.
Post Wash Tank (Electricity/Natural Gas)	No	The post-wash tank is natural gas-fired for one factory but electrically heated for others. Depending on the configuration of the particular factory, the electricity or natural gas consumption should be

		measured. If natural gas-fired, the electricity consumption of the auxiliary equipment should also be measured separately. The heating banks and all auxiliary equipment should be measured together if electrically heated.
Holding Tank (Electricity)	Yes	This is for holding some molten salt to be used in case of maintenance. It can be turned off and emptied and only put on when needed during maintenance, and it is not a priority to measure.
Gantry (Electricity)	Yes	The gantry consumes very little energy and can be excluded from the measuring systems.
Nitrogen Generation (Electricity)	Yes	If the plant has an on-site generation unit to produce its nitrogen, then the electricity consumption of that unit should be measured.
Nitrogen Generation (Nitrogen)	Yes	The amount of nitrogen produced and consumed should be measured.

4.2. Case Carburizing (Location B)

The Location B Plant runs case carburizing and bainitic hardening in different channels. This study was done on the case carburizing channel only. The case carburizing channel mainly produces train-bearing units for the railway industry with one outer ring and two inner rings per bearing. The rings are carburized to a case depth of 1.5 – 3 mm. The scope and process flow chart of this process is shown in Figure 15 below and has two sections. The first section is the carburizing line, where the pit furnace, salt quench, air cooling, and salt washing are located. The first section carries out the primary process of carbon diffusion into the steel component. The second section consists of the rehardening furnace, oil quenching, alkali washing, deep cooling, drying, and tempering furnace.

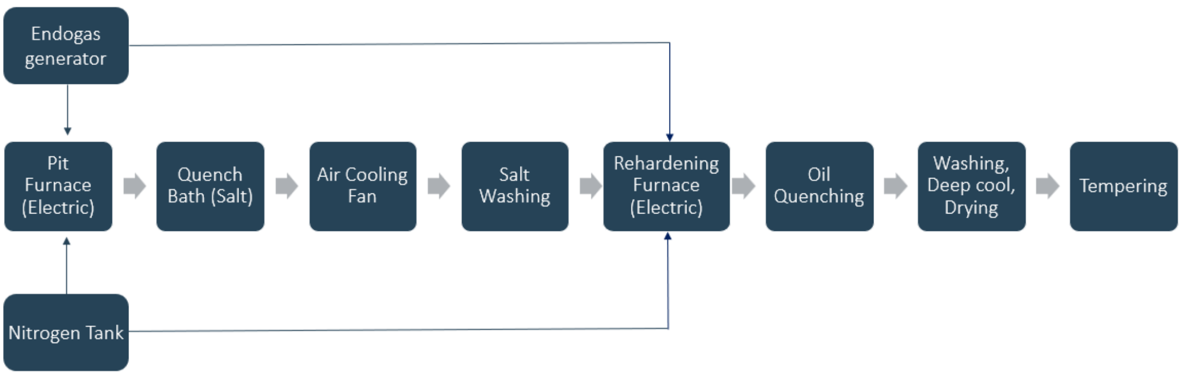

Figure 15: Case Carburizing process flow (Location B).

Both lines have different maximum capacities and carrier weights. The initial plan during the design stage was to install two pit furnaces and one big rehardening furnace to accommodate the product flow through the two pit furnaces. But, currently, only one pit furnace has been installed and is running production with the big rehardening furnace. As production volumes have risen beyond the current capacity, plans are being made to install a second pit furnace or a low-pressure vacuum furnace.

The soft rings are first verified to ensure the receipt components are intact, then loaded into the pit furnace for heating and carbon diffusion. Unlike the through-hardening process, there is no pre-wash before the furnace in this process. The pit furnace is an electrically fired furnace that operates under atmospheric pressure. It has a risk of decarburization due to air inflow from the environment affecting the furnace atmosphere. Decarburization is carbon loss at the surface of the steel material due to lower carbon content and activity in the furnace atmosphere. This will result in lower hardness of the steel material and is avoided by injecting gases into the furnace to serve as a protective and active atmosphere. This protective atmosphere will also prevent air or oxygen from entering the furnace, avoiding oxidation or scaling. Here, A mix of endogas and nitrogen is used as the protective atmosphere. This contains CO, CO_2, H_2, N_2, and CH_4. The endogas is produced from the incomplete combustion of natural gas using the endogas generator with a nickel catalyst.

Pressurized natural gas is also continuously added to the furnace as a carbon source for the carbon diffusion process, and the carbon potential of the furnace atmosphere is maintained at 1.3%. The carburizing and diffusion process takes about 15 hours in the pit furnace, after which the material is quickly transferred to a salt bath with agitation for quenching. After quenching, it is air-cooled and washed. The next process starts in the roller hearth (RH) rehardening furnace, where the material is heated. The rehardening furnace has the same protective atmosphere as the pit furnace and is supplied by the same endogas generator. After rehardening, it is quenched in oil and washed using alkali concentration water. It is then washed, rinsed, and deep-cooled. The final process involves drying using hot air and then tempering.

4.2.1. Production Data

To map the energy consumption, the production data and utilization of the factory were evaluated. The production data for 2022 was made available by the process development specialist for the location B factory. The utilization values were calculated based on the maximum capacity of the pit furnace line since that is the rate-determining step in the whole process. The rate-determining step means the step that takes the longest time and is the slowest; hence every other step's speed is dependent on it because no matter how fast the other steps are, they have to wait for the slowest step, and that determines the speed or rate of the entire process. The equation for calculating the utilization is shown below:

$$\frac{Weight\ of\ material\ produced\ per\ month}{maximum\ operating\ capacity\ per\ batch * maximum\ batches\ per\ month} * 100\%$$

$$\frac{X\ kg/month}{X\frac{kg}{batch} * X\frac{batches}{month}} * \ 100\%$$

The maximum calendar hours were considered during the utilization calculation. The utilization value for October was low due to a lack of production material.

There are differences between the pit furnace line and the rehardening furnace line production data due to time lags in the process flow. The pit furnace line takes long hours, sometimes leading to products being treated and recorded in this process in a particular month and ending up being treated and recorded in the next month for the rehardening process. Figure 16 shows the variation in weight utilization across the different months.

The utilization values for production weight and run time were reasonably stable from January to September, but they went down drastically in October because of a lack of production demand. Both run time and production weight show the same trend pattern, but the run time utilization values are higher than that of product weight, and this is because the run time includes the production hours and the quality adjustment hours. Quality adjustment hours are used to conduct soot burn and temperature uniformity surveys inside the furnace. There is no production during this time, but the furnace is on and consuming energy. Soot burn is the addition of air to the furnace to burn off any residual carbon monoxide in the furnace to form methane. A temperature uniformity survey is done using a thermocouple to check the inner walls of the furnace and ensure the same temperature.

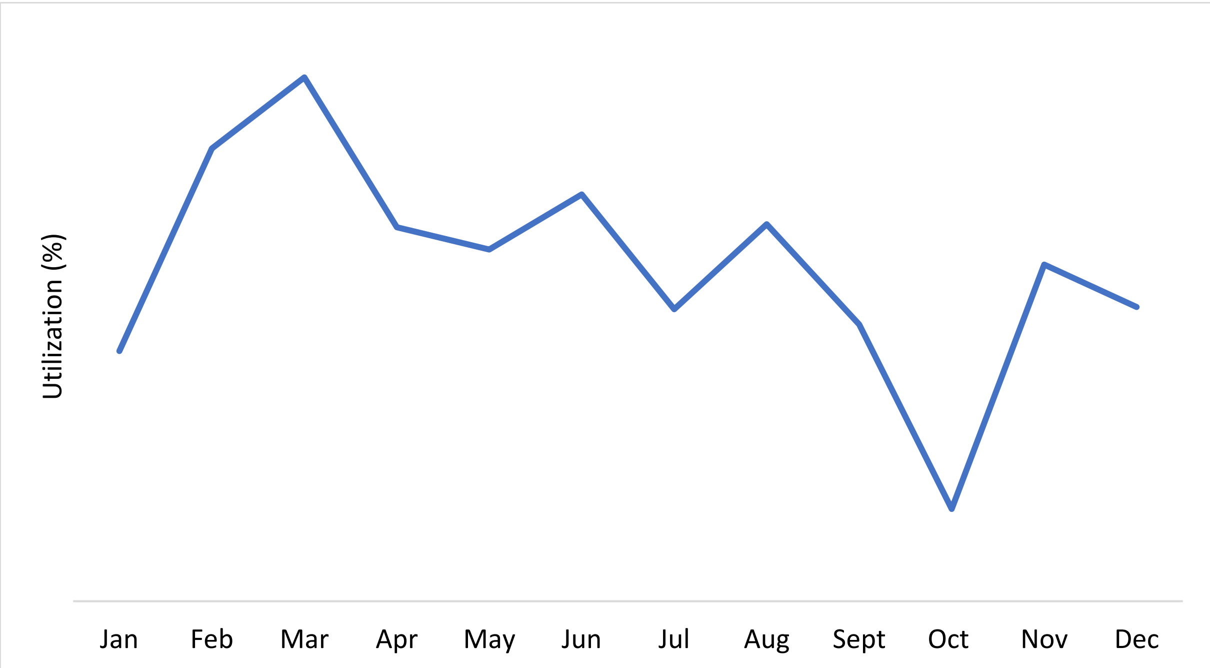

Figure 16: Graph showing weight utilization for location B

4.2.2. Energy Data

The energy consumption data for the location B Plant is obtained from the installed Energy meters, where the data is logged and stored. The data was made available by the process development specialist for location B. Not all equipment in location B has separate meters logging its energy consumption, but there is a main meter that logs the electricity consumption of each section. This is why the pit furnace, salt quench tank, air cooling fan, and washing tank have their values together. The rehardening furnace, oil quench tank, washing (alkali wash, rinse, deep cooling, drying), and tempering units have one meter, so their values are together too. The energy data includes all auxiliary equipment attached.

The natural gas consumption is logged by flow meters. This process has three main natural gas consumers: the carbon diffusion in the pit furnace, the rehardening furnace's protective atmosphere, and the endogas generator to produce endogas. There is no meter continuously recording the natural gas consumption of the endogas generator; hence the natural gas consumption is estimated based on the flow meter reading of the hourly consumption. The endogas generator's electricity and natural gas consumption is constant monthly because the equipment produces the same amount of endogas monthly, and any excess generated is flared. The endogas generator supplies endogas to the case carburizing process and another bainitic hardening process. The endogas generator's total electricity and natural gas consumption were split using volume allocation. The case carburizing process uses about 60% of the total endogas generated. The natural gas consumption values in m^3 were converted to energy values in kWh by using the relationship that 1 Nm^3 equals 10 kWh.

Nitrogen is bought from Linde Gas company, which produces nitrogen using the pressure swing adsorption (PSA) process. The nitrogen is supplied to SKF at 98 to 99.9999 vol. % purity (Linde Engineering, 2023). The nitrogen consumption values in m^3 were converted to energy values in kWh by using the relationship that 1 Nm^3 equals 0.4 kWh (Styles, 2022).

4.2.3. Theoretical Energy Demand

This is achieved by carrying out an energy balance around each piece of equipment in the system using the energy conservation law. The law of energy conservation, also known as the first law of thermodynamics, is a fundamental principle of physics that states that energy cannot be created or destroyed, only transformed from one form to another. In other words, a closed system's total energy remains constant over time. This law is based on the principle of conservation of mass and energy, which suggests that the sum of total mass and energy in a system is constant. This study is focused on thermal energy as this is a heat treatment process. The Thermodynamic equation for heat transfer is given as follows.

$$Q = m\, c_p\, \Delta T$$

Where Q = amount of heat transferred (gained or lost) by the material in joules (j)
m = mass of material in kilograms (kg)
C_P = specific heat capacity of the material in j/kg/°C
ΔT = change in temperature in °C

This equation was used to calculate the energy required for heating up (heat gained) or cooling down (heat lost) the steel-bearing material at each stage of the heat treatment process. The carburizing gas diffused into the material is not considered as the quantity is negligible. The total energy required for all stages of the case carburizing heat treatment process under ideal conditions was obtained as 0.45 kWh/kg. The difference between this value and the measured value shows how much energy is lost in the process and the possible energy-saving potential. It gives a theoretical benchmark for energy-saving implementations.

4.2.4. Key Performance Indicators (KPIs)

Choosing a KPI for the case carburizing process was decided, considering the process runs with different product class mixes simultaneously at any point in the furnace. Even though the case carburizing channel mainly produces train-bearing units (TBUs), three different classes of TBUs are produced: class E, class K, and class G. So, using a product-based KPI would be impossible as one cannot split the energy data across the various product class mixes due to the different recipes and specifications. A theoretical energy demand calculation was done on the process, and the results show that the process's energy consumption largely depends on the masses of the products rather than their individual properties. Also, the recipes indicating the time and temperatures the product batches spend in each step process largely depend on the mass.

Hence, using a time-based KPI, such as Total Energy (kWh/yr), and a mass-based KPI, such as Specific energy consumption (kWh/kg), becomes the best possible solution for representing the results of this analysis. It also ensures that the results can be compared to other heat treatment processes with the same KPI. The equation for calculating the specific energy consumption is shown below:

$$\frac{Total\ energy\ consumed\ per\ month\ in\ kWh}{Total\ weight\ produced\ per\ month\ in\ kg}$$

The KPI results cover the product and the carrier weight. If the carrier weight is removed, the KPI values drop by 27%. Figure 17 shows the variation in the specific monthly energy consumption.

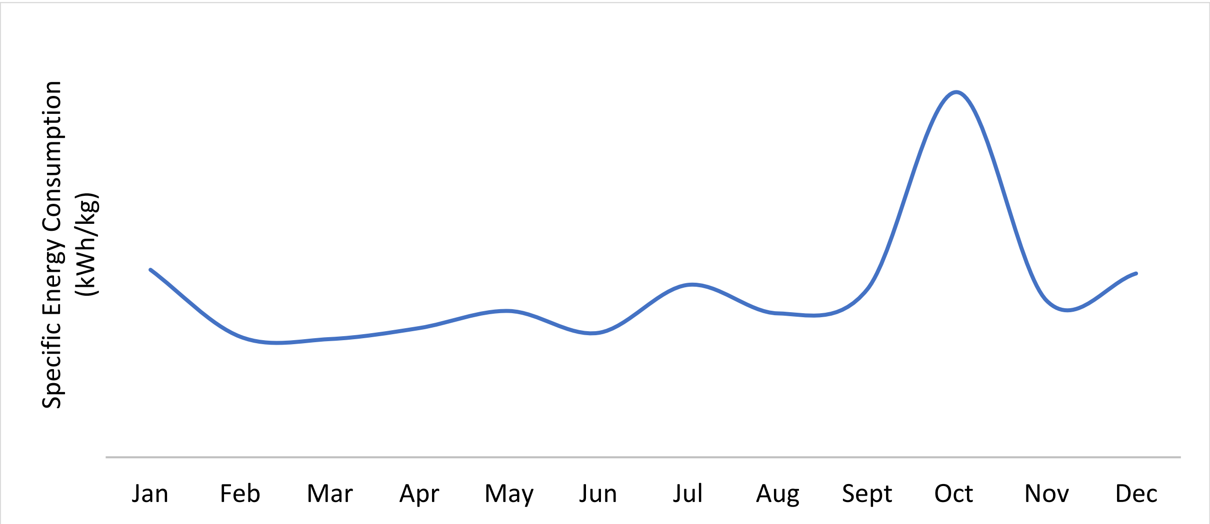

Figure 17: Specific Energy consumption for the different months in 2022 for Case carburizing.

A trend can be seen across the months except for October, when 443 production hours were lost due to lack of material, which was an outlier to the results shown in other months.

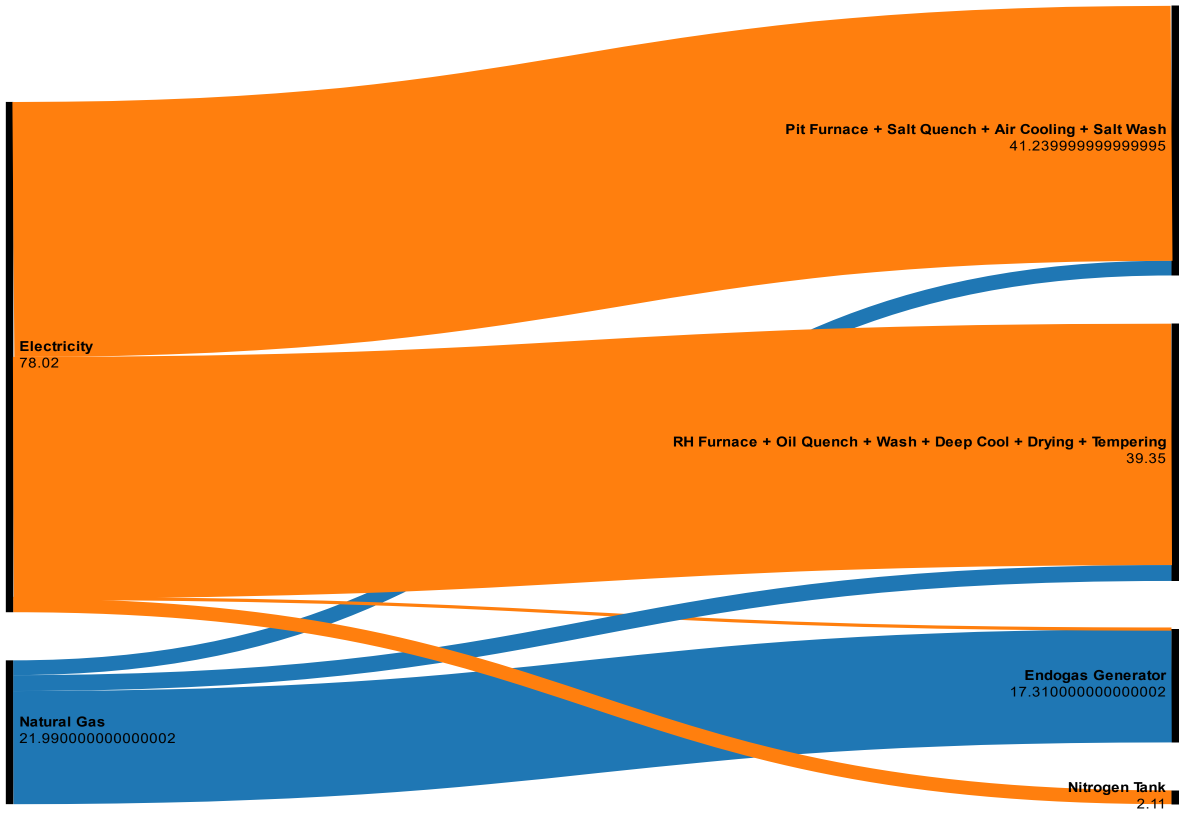

Figure 18: Sankey diagram showing the % distribution of energy consumption for Case carburizing.

Figure 18 shows the way the energy consumption of each piece of equipment is split across different energy sources and their relative percentages. Natural gas accounts for 22% of the total energy consumption, while electricity accounts for 78%.

4.2.5. Regression Modelling

The location B plant for case carburizing operates at a much higher utilization than location A for through-hardening. To make the KPI values in this analysis comparable to other heat treatment processes, values showing the same utilization must be used for the different processes, as utilization affects a plant's energy consumption. The results show that the utilization has an inverse relationship with the specific energy consumption. As the utilization increases, the specific energy consumption reduces, and vice versa. Higher utilization can drastically reduce the specific energy consumption of the plant. Hence a regression analysis (figure 19) was carried out to predict the specific energy consumption at different utilization rates. Four regression models, namely linear, power, exponential, and polynomial, were used to try to fit the data, and the power regression model fits the data best. An equation that related utilization to specific energy consumption was obtained. It was used to predict the specific energy consumption at 100% utilization of the normal operating capacity of the plant. Hence, 31% of the current energy consumption can be reduced if the furnace has higher utilization.

The equation relating Specific Energy Consumption to Utilization:

$$y = A\, x^{-b}$$

where y = Specific Energy consumption in kWh/kg
and, x = Utilization in %
A and b are constants

The R-squared value of 0.9015 and the randomness of the residual plot of the predicted Y-values show a good fit between the power regression model and the measured data.

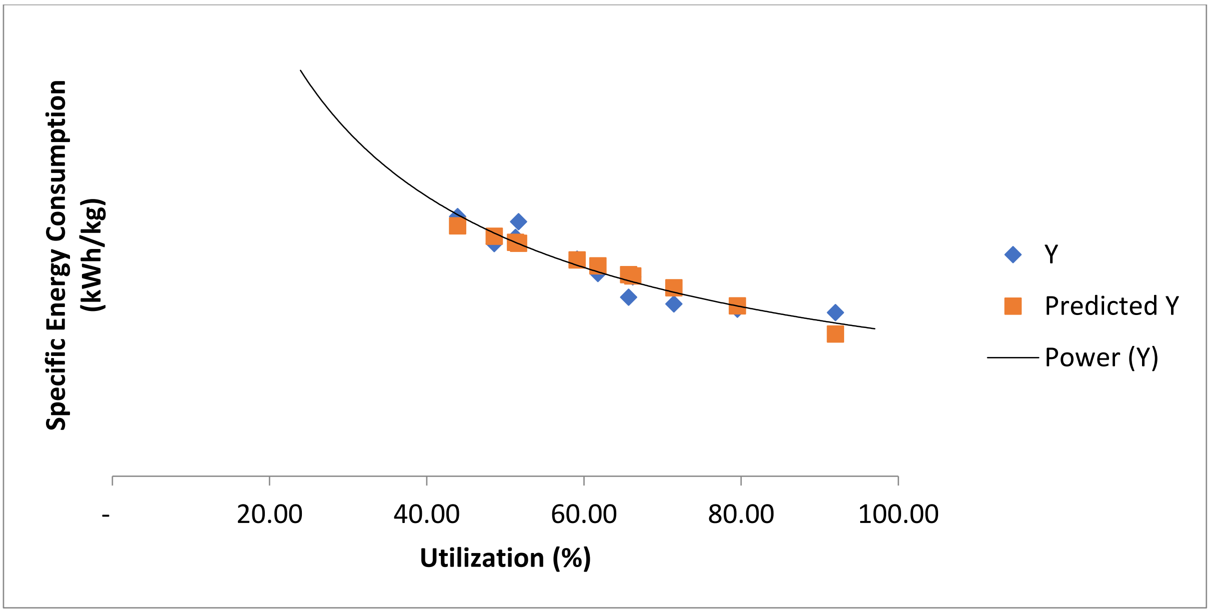

Figure 19: Regression plot of specific energy consumption against utilization for case carburizing.

4.2.6. Environmental Impact

The national electricity grid is the source of the electricity used at location B. Its electricity mix includes coal, natural gas, nuclear, hydroelectric, and renewable sources such as wind and solar. Coal is the dominant electricity generation source, accounting for approximately 70% of the total electricity generated. The emissions from coal-fired power plants are a significant contributor to greenhouse gas emissions in the country. The natural gas consumed is sourced from Adani Gas Ltd. The energy and emissions performance report from SKF's EHS Team for 2022 shows that the CO_2 emissions factor for the location B plant's electricity is 692.7 g CO_2-eq/kWh_{el}, and that of natural gas is 193.9 g CO_2-eq/kWh (EHS Team, AB SKF, 2022). These values only cover scope 1 and 2 emissions as scope 3 emissions are challenging to measure by the site. The equation for calculating the carbon intensity is:

$$Carbon\ Intensity = Emmision\ coefficient * specific\ energy\ consumption$$

These values can be used to estimate the environmental impact of the energy consumption of the case carburizing heat treatment process in terms of greenhouse gas emissions. Figure 20 shows that despite natural gas contributing 22% of energy consumption, it accounts for only 7% of the emissions.

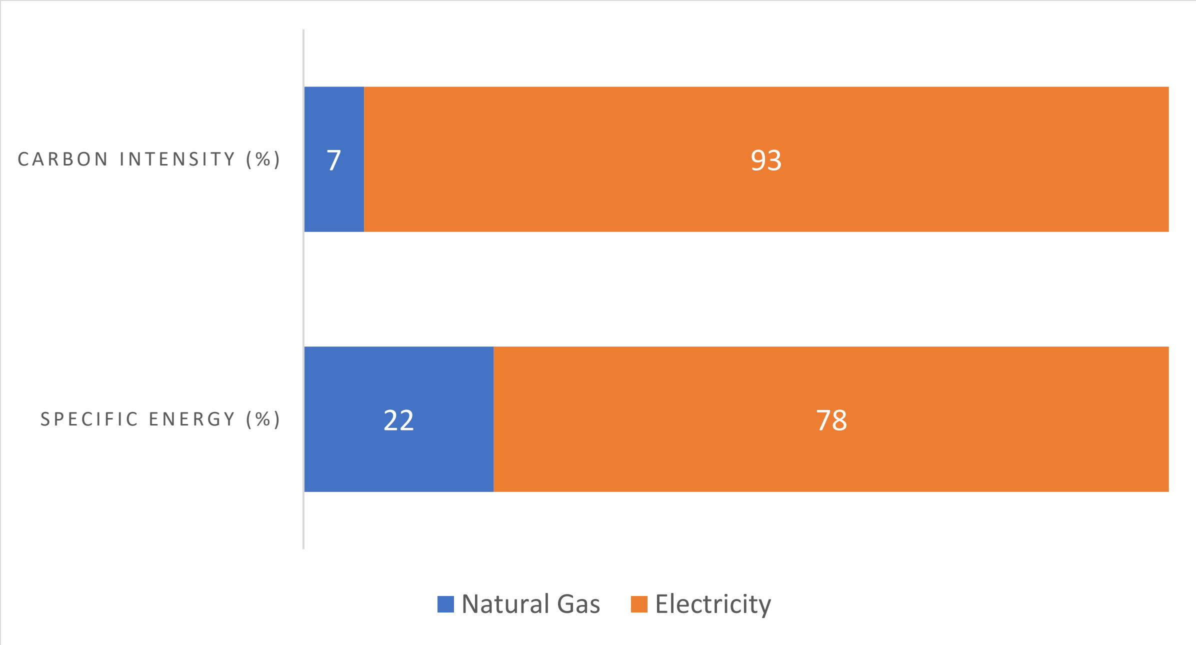

Figure 20: Environmental impacts of Through hardening process

Electricity has a high environmental impact because it is sourced from coal, and this is an avenue for improvement in electricity sources. It also shows that switching from natural gas-fired furnaces to electrically heated ones is not always the best environmental case if the electricity mix is bad.

4.2.7. Summary of Results

The results show that 84% of the current energy consumption is energy loss to the environment from the process, 27% of the energy consumption is lost to the carrier weight, 31% of energy consumption can be reduced by optimizing the utilization, and 53% of the energy consumption can be reduced theoretically by implementing energy savings and energy efficiency.

4.2.8. Energy Metering

Energy meters cannot be installed at every point due to financial constraints. Some points are critical and need to be measured, while others are either not critical or can be calculated from other metered points. Table 2 below shows the list of possible metering points for the location B case carburizing process with explanations of their level of priority or criticality.

Table 2: Energy metering for the case carburizing process.

Equipment	Currently Measured	Comments
Central Meter (Electricity)	No	This central meter measures the total electricity consumption of all equipment connected to the heat treatment process. This is very important as it helps to have a holistic idea of the electricity consumption of the entire process. It also helps in auditing each

		piece of equipment's electricity consumption to be sure the values they show add up to the central meter value. It can also help estimate the electricity consumption of equipment that doesn't have meters attached to them by subtracting the sum of the other equipment from the central meter value.
Central Meter (Natural gas)	No	This central meter measures the total natural gas consumption of all equipment connected to the heat treatment process. This is very important as it helps to have a holistic idea of the natural gas consumption of the entire process. It also helps in auditing each piece of equipment's natural gas consumption to be sure the values they show add up to the central meter value. It can also help estimate the natural gas consumption of equipment that doesn't have meters attached to them by subtracting the sum of the other equipment from the central meter value.
Channel Meter Pit Furnace Line (Pit Furnace + Salt Quench + Air cooling fan + salt wash tank) (Electricity)	Yes	This channel meter measures the electricity consumption of all equipment connected to that channel. This is beneficial in cases where measuring meters cannot be attached to all equipment due to financial constraints, but it has the disadvantage of not being able to show the energy performance of each piece of equipment.
Channel meter Rehardening furnace Line (RH Furnace + Oil Quench + Washing + deep cool + drying + Tempering) (Electricity)	Yes	This channel meter measures the electricity consumption of all equipment connected to that channel. This is beneficial in cases where measuring meters cannot be attached to all equipment due to financial constraints, but it has the disadvantage of not being able to show the energy performance of each piece of equipment.
Carburizing Furnace (Electricity)	No	The carburizing furnace is the most critical equipment of the process as it carries out the primary heating process and consumes the most energy. For a natural gas-fired furnace, this electricity measurement is for all auxiliary equipment like drives, roof fans, exhaust fans, and combustion fans connected to the furnace. This

		meter would include the heater and the auxiliary equipment for an electrically heated furnace.
Carburizing Furnace (Natural Gas)	No	The natural gas used for the burners should be measured for a natural gas-fired furnace. Also, if any natural gas is added as part of the protective atmosphere, that should be measured too. This is essential to see the natural gas consumption rate for studies on the impact of using natural gas-fired burners or electric heaters.
Rehardening Furnace (Electricity)	No	The rehardening furnace is the second most critical equipment of the process as it carries out the secondary heating process and consumes significant energy. For a natural gas-fired furnace, this electricity measurement is for all auxiliary equipment like drives, roof fans, exhaust fans, and combustion fans connected to the furnace. This meter would include the heater and the auxiliary equipment for an electrically heated furnace.
Rehardening Furnace (Natural Gas)	No	The natural gas used for the burners should be measured for a natural gas-fired furnace. Also, if any natural gas is added as part of the protective atmosphere, that should be measured too. This is essential to see the natural gas consumption rate for studies on the impact of using natural gas-fired burners or electric heaters.
Salt Quench Tanks (Electricity)	No	This is the third-highest energy consumer that consumes a lot in keeping the salts molten. The tanks are also open, so they have lots of heat loss. The energy meter should include electric heater banks and other attached auxiliary equipment like agitators.
Oil Quench Tanks (Electricity)	No	The oil quench tanks consume considerable energy because of the heat loss of the open tank and oil. The energy meter should include all auxiliary equipment like heaters, agitators, drives, elevators, dampers, fans, and rollers attached to the tank.
Tempering Furnace (Electricity)	No	The tempering furnace should be measured to see how much electricity it consumes compared to the carburizing and rehardening furnaces.

Endogas Generator (Natural Gas)	Yes	This is a high consumer of natural gas, and it is essential to know how much natural gas is for gas-fired burners and how much is for endogas production.
Endogas Generator (Electricity)	Yes	This is not a top consumer. But it is relevant to see the difference between implementing different endogas generation configurations and sources.
Salt-wash Tank (Electricity/Natural Gas)	No	The Salt-wash tank can be natural gas-fired or electrically heated. Depending on the configuration of the particular factory, the electricity or natural gas consumption should be measured.
Air-cool Fan (Electricity)	No	This is an air-cooling fan for material at high temperatures, and it might be consuming considerable energy and should be evaluated.
Oil Wash Tank (Electricity/Natural Gas)	No	The Oil-wash tank can be natural gas-fired or electrically heated. Depending on the configuration of the particular factory, the electricity or natural gas consumption should be measured. If natural gas-fired, the electricity consumption of the auxiliary equipment should also be measured separately. The heating banks and all auxiliary equipment should be measured together if electrically heated.
Deep cool (Electricity)	No	This chiller system cools the material from about 50°C to 5°C. It might be consuming considerable energy and should be evaluated.
Drying (Electricity)	No	The dryer uses hot air, which requires heating and might consume considerable energy and should be evaluated.
Nitrogen Generation (Electricity)	No	If the plant has an on-site generation unit to produce its nitrogen, then the electricity consumption of that unit should be measured.
Nitrogen Generation (Nitrogen)	Yes	The amount of nitrogen produced and consumed should be measured.

4.3. Surface Induction Hardening (Location C)

The location C factory runs surface induction hardening on HUB 3E units for the automotive industry. Only the flanged outer and inner rings are heat treated at this factory. There are two separate heat treatment furnaces for the FOR and FIR in channel 3.7. Each furnace consists of hardening, quenching, fan drying, tempering, cooling, and final drying stations (Figure 21). The FOR and FIR furnaces have the same process flow but different power and cycle time for the various process steps. Surface induction hardening is relatively fast as the process times are in seconds compared to through hardening or case carburizing, which takes hours to days. This study was done on both FIR and FOR furnaces as the data measurement on site is done together.

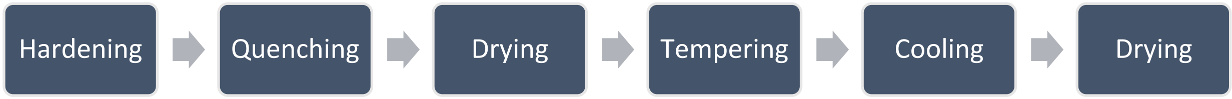

Figure 21: Induction hardening process flow (Location C).

The process flow for FIR and FOR follows the same type of equipment; the only difference is the power and the cycle time used, which changes for each step depending on whether it is FIR or FOR being treated. The material flow starts with the loading, which robots do automatically. Dimensions are measured next to ensure the products are within specifications before the hardening process starts. The induction coil gets in position and heats the material quickly to harden it. The hardening is a surface hardening process, so the material is heated up to just on the immediate surface. It is not through heated to the core, as in through hardening or case carburizing. After hardening, the material is quenched using a mixture of water and polymer at a high flow rate. Drying is done immediately with coolers using 4-6 bar of compressed air, and the material moves to the tempering station. The tempering is done in 2 stages with the same cycle time and power. After tempering, a water shower is used to cool down the material, and then drying is done again. The products are then unloaded by robots and sent to the next stage for machining.

4.3.1. Production Data

The production data and utilization of the factory are essential in mapping energy consumption. The production data for 2022 was collected by the process development engineer for the automotive market in location C. The production at location C is done six days a week, with Monday to Friday being full production days, Saturday being half-day production, and Sunday being an off day. The production values were recorded in the number of assemblies and were converted to kg using the masses of the FOR and FIR.

The equation for calculating the utilization is shown below:

$$\frac{number\ of\ assemblies\ produced\ per\ month * weight\ of\ FOR + FIR\ per\ assembly}{\left(\frac{maximum\ number\ of\ assemblies\ per\ year * weight\ of\ FOR + FIR\ per\ assembly}{number\ of\ months\ per\ year}\right)} * 100\%$$

$$\frac{X\,\frac{assemblies}{month} * 3.0843\,\frac{kg}{assembly}}{\left(\frac{X\,\frac{assemblies}{year} * 3.0843\,\frac{kg}{assembly}}{12\,\frac{months}{year}}\right)} * 100\%$$

The utilization values were calculated based on the maximum capacity of the channel. The maximum calendar hours were considered during the utilization calculation. Figure 22 shows the variation in utilization across the different months.

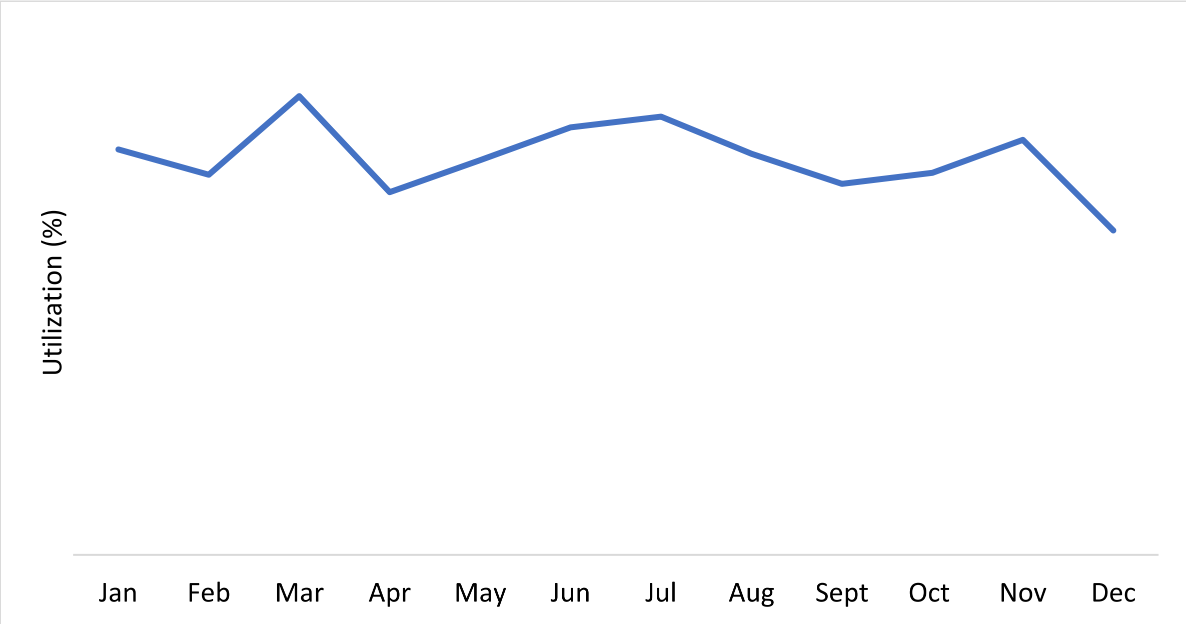

Figure 22: Graph showing utilization for the location C factory.

4.3.2. Energy Data

The location B plant uses only electricity, and no gases are used. The energy consumption data for the Plant is obtained from the substation Energy meters, where the data is logged and stored. The process development engineer for the automotive market in location C made the data available. The FOR and FIR furnaces do not have an energy meter measuring their energy consumption separately. There is only one substation level energy logging where the furnaces, turning machines, marking dot machines, welding workshop, and assembly areas are connected together. But calculations done by the electrical engineers show that the FOR and FIR furnaces consume 80% of the logged substation energy. The energy data is logged in terms of average power in kW every 5 mins. A daily power average is multiplied by 24 hours to get the daily kWh. There is no logging of the various equipment separately. The data is only available from April 2022, so no data is logged in for January to March 2022. The energy data includes all auxiliary equipment attached.

4.3.3. Theoretical Energy Demand

This induction hardening is a surface hardening process whereby the materials are heated only on the surface to a particular depth using power-driven induction coils. Therefore, the first law of thermodynamics will not work directly here in calculating the theoretical energy demand as the law considers the material's total mass and the temperature difference. The mass of the material heated is gotten as 20% of the total mass using simulations. And this is used to calculate the theoretical energy demand using the first law of thermodynamics. The power law is used for processes like drying, where heat is not transferred since the fan has a rated power and cycle time. Power is the rate of energy transfer or work done; therefore, energy is equal to power multiplied by time.

$$E = Pt$$

where E = Energy in kWh, P = Power in kW, t = time in hrs.
This equation was used to calculate the energy required for heating up (heat gained) or cooling down (heat lost) the steel-bearing material at each stage of the heat treatment process. The total energy required for all stages of the case carburizing heat treatment process under ideal conditions was 0.114 kWh/kg. The difference between this value and the measured value shows how much energy is lost in the process and the possible energy-saving potential. It gives a theoretical benchmark for energy-saving implementations.

4.3.4. Key Performance Indicators (KPIs)

Choosing a KPI for the surface induction hardening process was decided, considering the process runs only one product type. Hence, a product-based KPI such as kWh/piece can be used. But the energy data from the location C factory shows that the FOR and FIR furnaces have their energy data together. Since both don't have the same weight, it becomes impossible to split the energy data down to the product level. For other factories, where the FOR and FIR furnaces have their energy data measured separately, kWh/piece is a good KPI. For the location C factory, The next best possible KPI comparable with the results from the other heat treatment processes being studied is a mass-based KPI, the Specific energy consumption (kWh/kg). A time-based KPI such as total energy (kWh/yr) could not be used for the location C factory because the energy data for 2022 is only available from April to December. Also, since only the surface is heated here to a certain depth, kWh/kg of product heated cannot be used like in other processes. Instead, kWh/kg of total product weight is used so that the KPI results are the same and comparable to the other heat treatment processes. The equation for calculating the specific energy consumption is shown below:

$$\frac{Total\ energy\ consumed\ per\ month\ in\ kWh}{Total\ weight\ produced\ per\ month\ in\ kg}$$

Figure 23 shows the variation in the specific monthly energy consumption. A relatively stable trend can be seen across the months.

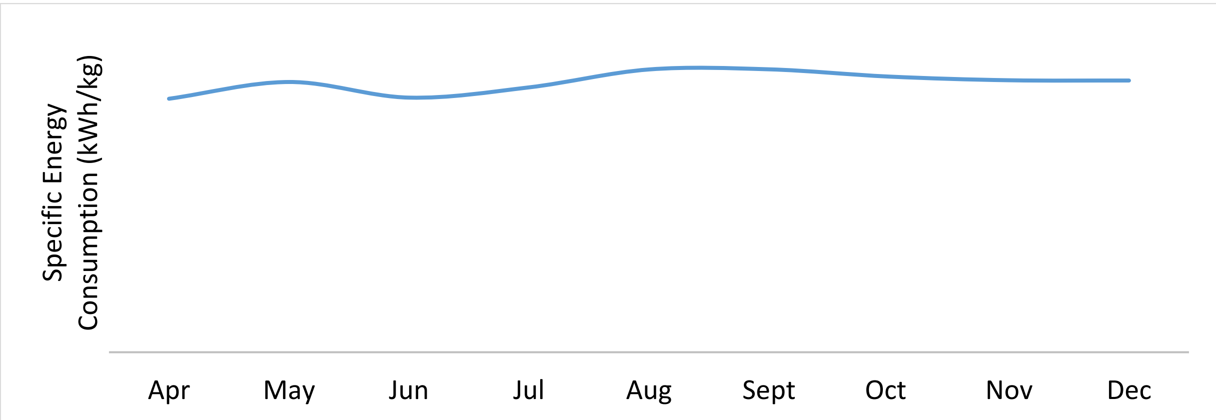

Figure 23: Specific Energy consumption for the different months in 2022 for Induction hardening.

The energy data for the location C plant could not be gotten on an equipment basis level. Hence there is no Sankey diagram here showing the energy performance of each piece of equipment, like in the through hardening or case carburizing studies.

An energy mapping study was also done on the induction hardening factory in location D. The analysis was done by taking momentary measurements using external measuring and monitoring equipment, as there is no online continuous measuring system. The measurements were done on a detailed level on three different channels, with the hardening station, tempering and utilities measured separately. The values obtained there are similar to that obtained from the induction hardening study in location C and show that the results in the location C study are within the correct range despite the level of uncertainty in the energy data collection.

4.3.5. Regression Modelling

The location C plant operates at a much higher utilization value compared to the location A factory for through hardening or the location B plant for case carburizing. To make the KPI values in this analysis comparable to other heat treatment processes, values showing the same utilization must be used for the different processes, as utilization affects a plant's energy consumption. The results show that the utilization has relatively less impact on specific energy consumption for induction hardening. As the utilization increases or reduces, the specific energy consumption remains roughly the same.

A regression analysis (figure 24) was carried out to predict the specific energy consumption at different utilization rates. Four regression models, namely linear, power, exponential, and polynomial, were used to try to fit the data, and the power regression model fits the data best. An equation that related utilization to specific energy consumption was obtained. It was used to predict the specific energy consumption at 100% utilization of the normal operating capacity of the plant. Hence, 1.4 % of the current energy consumption can be reduced if the furnace has higher utilization.

The equation relating Specific Energy Consumption to Utilization:

$$y = A\,x^{-b}$$

where y = Specific Energy consumption in kWh/kg
and, x = Utilization in %
A and b are constants

The R-squared value of 0.097 is low and shows that there is not a good fit between the power regression model and the measured data. This further indicates that utilization does not significantly affect the specific energy consumption for induction hardening.

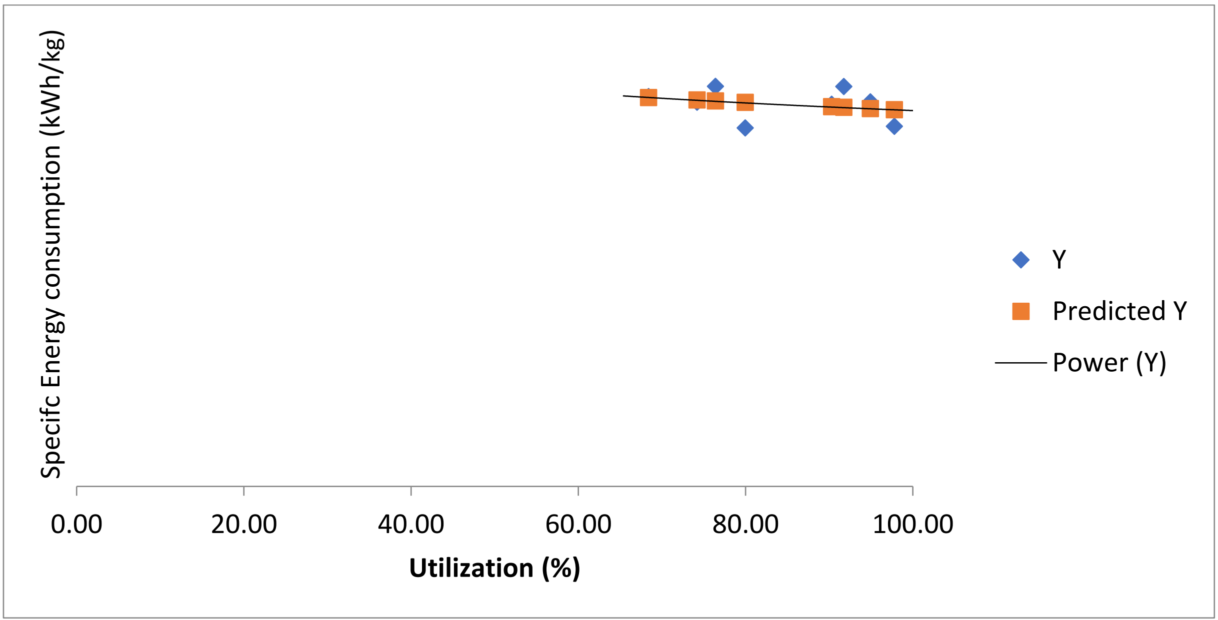

Figure 24: Regression plot of specific energy consumption against utilization for induction hardening.

4.3.6. Environmental Impact

Natural gas is the highest contributor to location C's electricity generation, followed by renewable energy sources such as hydroelectric, wind, solar, and geothermal. According to the National Center for Energy Control (CENACE), natural gas is location C's dominant electricity generation source, accounting for approximately 61% of the total electricity generated (Zaretskaya, 2020). The emissions from natural gas-fired power plants significantly contribute to greenhouse gas emissions. The energy and emissions performance report from SKF's EHS Team for 2022 shows that the CO_2 emissions factor for the location C plant's electricity is 399.7 g CO_2-eq/kWh_{el}, (EHS Team, AB SKF, 2022). These values only cover scope 1 and 2 emissions as scope 3 emissions are challenging to measure by the site. The equation for calculating the carbon intensity is shown below:

$$Carbon\ Intensity = Emmision\ coefficient * specific\ energy\ consumption$$

These values can be used to estimate the environmental impact of the energy consumption of the induction hardening heat treatment process in terms of greenhouse gas emissions.

4.3.7. Summary of Results

The results show that 61% of the current energy consumption is energy loss to the environment from the process, 1.4% of energy consumption can be reduced by optimizing the utilization, and 59.6 can be reduced theoretically by implementing energy savings and energy efficiency.

4.3.8. Energy Metering

Energy meters cannot be installed at every point due to financial constraints. Some points are critical and need to be measured, while others are either not critical or can be calculated from other metered points. Table 3 below shows the list of possible metering points for location C, Induction hardening process, with explanations of their level of priority or criticality.

Table 3: Energy metering for the Induction hardening process.

Equipment	**Currently Measured**	**Comments**
Central Meter FOR +FIR (Electricity)	No	This central meter measures the total electricity consumption of all equipment connected to the heat treatment process's FOR and FIR furnaces. This is very important as it helps to have a holistic idea of the electricity consumption of the entire process. It also helps in auditing each piece of equipment's electricity consumption to be sure the values they show add up to the central meter value. It can also help estimate the electricity consumption of equipment that doesn't have meters attached to them by subtracting the sum of the other equipment from the central meter value.
FIR Furnace Meter Hardening + Quenching + Drying fan + Tempering + cooling + drying fan (Electricity)	No	This furnace meter measures the electricity consumption of all equipment connected to that channel. This is beneficial in cases where measuring meters cannot be attached to all equipment due to financial constraints, but it has the disadvantage of not being able to show the energy performance of each piece of equipment.
FOR Furnace Meter Hardening + Quenching + Drying fan + Tempering + cooling + drying fan (Electricity)	No	This furnace meter measures the electricity consumption of all equipment connected to that channel. This is beneficial in cases where measuring meters cannot be attached to all equipment due to financial constraints, but it has the disadvantage of not being able to show the energy performance of each piece of equipment.
Hardening station FOR/FIR (Electricity)	No	The hardening station is the most critical equipment of the process as it carries out the primary heating process and consumes the most energy. This meter would include the induction coil and the auxiliary equipment.
Quenching FOR/FIR (Electricity)	No	This spray nozzle system rapidly sprays water and polymer mixture on the hot material. The energy meter should include pumps, chiller systems, and other attached auxiliary equipment like agitators for the quench tank.

Drying FOR/FIR (Electricity)	No	The drying fan or compressed air cooler might consume considerable energy and should be evaluated. The quantity of compressed air used should also be measured.
Tempering FOR/FIR (Electricity)	No	The tempering station should be measured to see how much electricity it consumes compared to the hardening station.
Cooling FOR/FIR (Electricity)	No	This spray nozzle system sprays water and polymer mixture on the hot material rapidly to cool it. The energy meter should include pumps, chiller systems, and other attached auxiliary equipment like agitators for the quench tank.
Drying FOR/FIR (Electricity)	No	The drying fan or compressed air cooler might consume considerable energy and should be evaluated. The quantity of compressed air used should also be measured.

Currently, the location C factory only has measurements on the substation level, which includes the heat treatment furnaces, turning machines, marking dot machines, welding workshops, and assembly areas that are connected. There is no measurement on the heat treatment furnaces, only level. An approximate value of 80% was used to get the data for the heat treatment furnaces from the substation data.

5. Comparative study of the three heat treatment processes

5.1. Guidelines on Heat Treatment Energy Mapping

A vital aspect of every research methodology is repeatability and reproducibility. The results of this project should be able to be carried out by any other person, and the same results obtained. Also, SKF has over 140 factories around the world, and this study has shown that the results of one factory or plant might not be enough to place a label on a heat treatment process as the results of the study can change dramatically based on the location and specific processes carried out by different factories even though they are running the same heat treatment technology or process. Two factories in different locations both run the same case carburizing process. Still, results on their energy mapping values have shown that the results are quite apart. So many factors can cause this, ranging from the product mix, the energy performance of the specific equipment installed in that factory, the heat loss from the process, the energy management system in place, the way the operators run the process, the order of arrangement or plant layout of the factory, the environmental weather or climate.

Hence the energy mapping results of a particular factory or plant might only be able to be used for that specific factory and none other, even if they run the same heat treatment process. For some, like through hardening, the values might be within a range, and one factory study can label a heat treatment technology irrespective of the location. More studies might be required for different factories or sites to get more results. This is done to obtain a complete picture of the value variation across different locations. Hence, a guideline in addition to the methodology is pertinent to help each factory carry out an energy mapping of its factory. This guideline will be detailed, and any energy manager or factory personnel can follow it to carry out its energy mapping and get comparable values across different factories and technologies across SKF. The results will be reported in the same key performance indicator.

5.1.1. Scope and Boundaries

Define the vertical and horizontal scope and boundaries of the heat treatment process you want to study. Ideally, the horizontal scope of the heat treatment process should contain all processes between forming and machining for the particular heat treatment process. The vertical scope should include all energy inputs to the process, including electricity, natural gas, methanol, and nitrogen. All auxiliary equipment attached to each piece of equipment should be included in the study as usually there is only one meter measuring the energy consumption of a particular equipment or stage, and it captures all attached auxiliary equipment to that process. Not all systems in the heat treatment process are essential or significant to be considered. The main systems include heating, quenching, washing, cooling, and drying. All other non-essential systems like building heating, ventilation fans, transportation of materials, controls, and lighting should be excluded.

5.1.2. Inclusions and Exclusions

For an overall study, the energy consumption of the main meter connecting all equipment in the process is needed. But one must be careful to mention all included in this main meter measurement to make the results comparable. If a meter includes non-essential systems like building heating, ventilation fans, transportation of materials, and lighting, these must be deducted or mentioned in the report. But for more detailed studies, having data on the energy consumption of each piece of equipment is necessary. But in most cases, due to the financial constraints of installing measurement devices on all equipment, some devices have their measurements grouped or don't have one.

In these situations, one must get these equipment data by estimated calculations, the 30% rule of thumb (section 4.1.6), or deductions from the main meter readings. Estimated calculations are done when equipment does not have a continuous measurement device but has a simple flow meter or one has a manual hand-held measuring instrument. Then one can measure or record the flow or energy consumption in 1 hour or one day and use that value to estimate the consumption for a month or year. This is a rough value that would affect the sensitivity of the results and should be mentioned in the reports. The 30% rule of thumb is an approximate rule that says the energy consumption of equipment is usually within a 30% range of the installed capacity of the equipment, including all auxiliary equipment. It can be used for approximate estimations when a piece of equipment does not have a measuring device and no other way of estimating its energy consumption.

5.1.3. Process Flow

Identify the process flow of the heat treatment process being studied and take note of all energy inputs to all processes and equipment in terms of electricity, natural gas, nitrogen, methanol, etc. Draw a process flow chart and explain the entire process with details on what happens in each stage. Record the temperatures and times of each step in the process, which would be relevant to calculating the theoretical energy demand.

5.1.4. Production Data

Get the hourly, daily, or monthly production data in kg for the process for an entire year or month or whatever time frame the study was decided to be carried on. If the production data is not recorded in a concise time frame, clean the data and group the data into a constant regular time frame. Each piece of equipment would not have the same capacity and might have different production data. This might be tricky but worry not. The production data you need is the one from the rate-determining step. The rate-determining step in the process is the slowest or takes the longest time and is usually called the bottleneck operation. This step defines the speed or rate at which the entire heat treatment process proceeds, as all other steps have to wait for that step to be finished to proceed. This step is usually the furnace in most heat treatment processes. Collect data on the maximum capacity of that equipment, too, in this case, the furnace.

5.1.5. Utilization

Calculate the maximum production capacity of your process for the time frame your study is based on using the maximum capacity value and calendar hours. Divide the production data by the maximum production capacity and multiply by 100 to get the utilization of the factory in percentage.

$$\frac{Weight\ of\ material\ produced\ per\ time}{Maximum\ operating\ weight\ capacity\ per\ time} * 100\%$$

Some factories might also want to use scheduled hours to calculate their utilization. The scheduled hours are obtained by taking out the days of no production from the calendar hours, which accounts for holidays, maintenance, lack of demand, or any other unaccounted downtime. This is interesting but not comparable, as different plants have different scheduled hours based on their country's holidays, planned maintenance hours, production demand, and management decisions. So, for comparative studies, use calendar hours. Record the utilization values per hour, day, month, year, or time frame relevant to your studies.

5.1.6. Energy Data

Get the electricity data of the main meter and each piece of equipment in kWh, depending on your available data level. Use estimated calculations or the 30% rule of thumb as explained earlier for equipment you can't find data on and mention that in your report’s sensitivity analysis. Collect data on the natural gas consumption and convert it to kWh using the conversion coefficient of 1 m^3 = 10 kWh. Do the same for any other energy-consuming gases like methanol or nitrogen your system uses. You can find conversion coefficients readily online to convert them from whatever units they are into kWh. Nitrogen conversion coefficients depend on the generation system in place. A pressure swing adsorption (PSA) system is 1 m^3 = 0.4 kWh, while a membrane system is 1 m^3 = 0.2 kWh. Add up all the electricity, gas, etc., data together to get the energy data for that equipment or that system on the hourly, daily, monthly, or whatever time frame your study is on.

5.1.7. Key Performance Indicators

One standard KPI will be used for all heat treatment processes; **Specific Energy Consumption in kWh/kg at a particular utilization in %**. To get this, divide the total energy data in kWh by the production data in kg for each of the different time frames the study is based on. You can get the specific energy consumption monthly if you want to study for an entire year. Or daily if you want to study for a month. Same for hourly basis if you want to study for a day. The specific energy consumption for each piece of equipment can also be obtained, just like that of the total process, if the energy consumption of each piece of equipment is recorded. This specific energy consumption is only peculiar to the current utilization value calculated earlier. If the utilization value changes, the specific energy consumption will change.

5.1.8. Regression Analysis

The specific energy consumption data must have the same utilization values for comparative studies. So, a regression analysis is required on the data to get an equation or formula representing the data and predicting its specific energy consumption at different or 100% utilization. Go to the data tab on Excel, go to data analysis on the top right, select regression, input the X values as the monthly or daily utilization values, and input the Y values as the monthly or daily specific energy consumption values. You get the line plot and residual plot. Edit the line plot chart, select the power regression model, and add the trend line for the Y values with the equation and R-squared values. The power equation relates the utilization values to the specific energy consumption values and will help predict the specific energy consumption at different utilization.

5.1.9. Normalization

For comparative studies, the values of the specific energy consumption must be normalized to be at the same utilization value using the equation obtained from the regression analysis. Decide on a utilization value at which you want to compare the different specific energy consumption values. This can be 100% or one of the compared results' utilization values. Input that utilization value into the equation as X values to give you the specific energy consumption (Y values) of that factory or heat treatment process at that utilization. Do this for all the different factories or heat treatment processes being compared and get their specific energy consumption values at the same utilization. Once all the specific energy consumption values are at the same utilization, they can be compared.

5.1.10. Carrier Weight

For carrier weight consideration and calculations, get the carrier weight value in kg and multiply it by the number of batches run within your study time frame. Add it to the production weight for that time frame of a study and use this value to divide the total energy consumption for that time frame of analysis. This would give the specific energy consumption when carrier weight is removed.

5.1.11. Theoretical Energy Demand

For processes involving through heating like bainitic hardening, martensitic hardening, and case carburizing, a theoretical energy demand calculation can be done using the first law of thermodynamics.

$$Q = m\, c_p\, \Delta T.$$

where Q = amount of heat transferred (gained or lost) by the material in joules (j),
m = mass of material in kilograms (kg),
C_p = specific heat capacity of the particular steel grade in j/kg/°C, which can be found online
ΔT = change in temperature in °C.

For each stage of the process, there is either heat loss or heat gain, and the amount of energy required to heat up or cool down the process can be calculated using the temperature of that step as T_2 and the temperature of the previous step as T_1. You get the Q value in joules and convert it to kWh by dividing by 3600000 and kWh/kg by dividing by the mass. Add up all the values gotten for all the steps together to get the value for the entire process.

For a surface heating process like induction hardening, a theoretical energy demand calculation can be done using the relationship between power, time, and energy since all the processes in induction hardening have a rated power and time duration. Power is the rate of energy transfer or the rate of work done; therefore, energy equals power multiplied by time.

$$E = Pt,$$

where E = Energy in kWh, P = Power in kW, and t = time in hrs.

This is done for each step, and the values obtained for all the steps are added together to get the value for the entire process.

5.2. Energy consumption

This study has shown that utilization is essential in comparing energy performance between different heat treatment processes. Looking at the current specific energy consumption values of through hardening, location A, and case carburizing, location B, it would seem that case carburizing consumes less energy. But looking at the fact that through hardening, location A operates at lower utilization than case carburizing, location B, it becomes evident that the values are not directly comparable.

Power regression models were used to fit and predict the specific energy consumption of the processes at different utilization to compare all three heat treatment processes studied on the same utilization level. Figure 25 shows the energy consumption variation of the three different heat treatment processes as utilization changes. The results show that case carburizing consumes considerably more energy than through hardening at the same utilization level. Case carburizing consumes 50-80% more energy than through hardening, depending on the utilization level being compared.

Surface induction hardening, however, shows less dependence on utilization than through hardening and case carburizing. If the decimal points of the surface induction hardening results are increased to 3 or 4, some slight relation with utilization can be seen. This is because the utilities, such as the chiller system cooling the quenching liquid, remain on irrespective of the utilization level. But since the quenching media is at 38°C, which is close to room temperature, there is less energy loss to the environment than through hardening or case carburizing with open tanks at high temperatures.

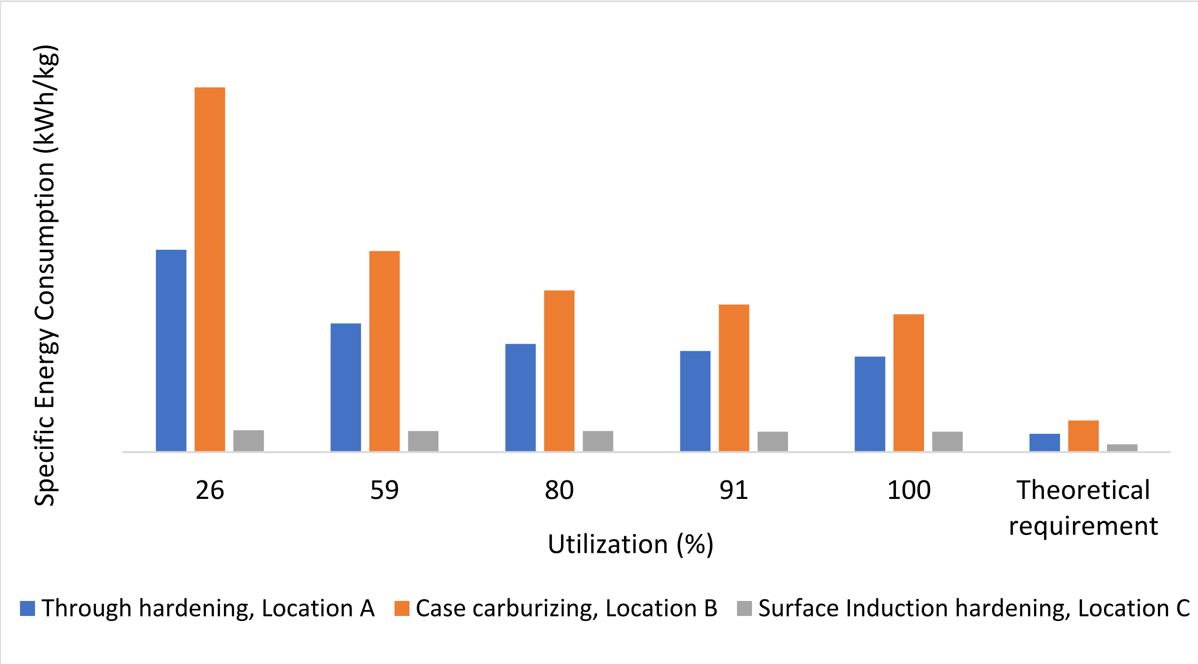

Figure 25: Comparison of energy consumption of the three heat treatment processes

Surface induction hardening consumes about 10% of the energy consumed by through hardening or case carburizing. Even though only about 10-20% of the full ring is hardened in this induction hardening process, its energy loss shows it is the most energy-efficient process. 84-91% of the energy used in through hardening or case carburizing is energy loss, while for surface induction hardening, it's 61%. From an energy point of view, surface induction hardening is the best as long as its product can achieve the same material properties and application as the other processes.

The theoretical requirement of each heat treatment process shows us that there is much potential in reducing the energy consumption of the processes further below their 100% utilization values. This is where energy savings and energy efficiency come in. Better insulation, burner efficiency, better burners, lids on the tanks, and heat recovery are some of the processes that can be used to improve the energy performance of the processes and reduce energy consumption.

Building heating was excluded in this study, but the variation in energy mapping results across different locations running the same heat treatment process shows that weather and climate play a role in the energy consumption of the entire process. In cold climate locations, the heat emitted or lost from the heat treatment process serves as building heating for the factory and reduces the need for additional district heating. This is the case for through hardening and case carburizing, where up to 80-90% of the energy is lost to the environment. But in the case of induction hardening, where less heat is lost, more heat would be needed to heat the building. The building heating analysis will be considered when a full factory study is done, as the factory floor contains heat treatment equipment and other processes like machining and assembly.

Studies on the carrier weight show that the location A factory, which has a low carrier weight, loses 4% of its energy consumption to the carrier weight. In comparison, the location B plant with a heavy carrier weight loses 27% of its energy consumption to the carrier weight. Hence, using lower carrier weights is very important in reducing the energy consumption of the different heat treatment processes.

5.3. Environmental Impact

Figure 26 shows the carbon Intensity of the different heat treatment factories.

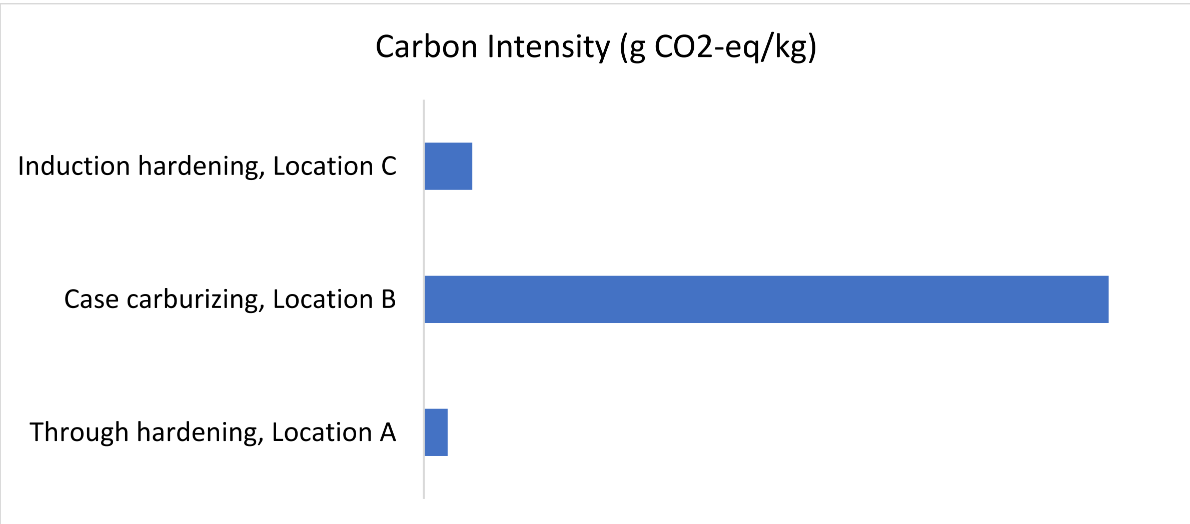

Figure 26: Comparison of the environmental impact of the heat treatment processes (scope 1, 2 and 3).

Case Carburizing in location B has the highest environmental impact in terms of g CO_2 eq/kg due to the electricity mix in the country. The electricity mix in location B is 70% coal, which is bad for the environment.

Surface induction hardening in location C produces relatively high emissions compared to its energy consumption. It consumes 10% of the energy consumption of through hardening, location A, but emits 100% more emissions. This is due to the electricity mix of location C being mainly natural gas dependent while location A is hydropower dependent. Natural gas power is a fossil fuel-based energy source and hence bad for the environment. Investing in cleaner energy sources is vital in reducing the greenhouse gas emissions of the different processes. SKF has to move entirely from fossil fuel sources and equipment in its operations to greener sources to improve its environmental footprint.

5.4. Limitations of the study

During this study, a series of challenges were faced that could potentially affect the sensitivity and accuracy of the results in representing the reality of the studied factories. Future energy mapping studies at SKF should overcome the problems listed below to increase the ease and accuracy of the study.

1. Some equipment in the locations A and B factories doesn't have measurement devices; hence the equipment's energy performance could not be studied.
2. There is no measurement logging for the natural gas consumption of the location A factory. Mass allocation was used on the natural gas logging to get location A data.
3. Data availability for the endogas generator system in the location B plant was limited, and approximate factors had to be used to split the data.
4. The nitrogen generator system for the location A factory has no meter measuring the consumption of each factory connected to it; hence approximations were used.
5. The availability of data in the location C plant is limited. The level of data in the location C plant is high at the substation level, and estimation was used for the furnace data.
6. There is no measurement device on the equipment level for the location C plant; hence equipment's energy performance study cannot be done on it.

5.5. Energy Improvements Recommendations

The following recommendations are proposed to improve the energy performance and environmental footprint of SKF's heat treatment processes:

- Switching from gas to electricity should be done considering the future electricity mix.
- SKF should invest in cleaner and greener energy sources across its factories to reduce its environmental footprint.
- Increased utilization & energy efficiency are necessary to reduce energy consumption.
- Lower carrier weight should be used in furnaces to reduce energy consumption.
- A study of one factory may not label the heat treatment process in all locations; hence further studies should be done across all factories in SKF using the detailed methodology & guidelines in the report.

6. Conclusion

Specific Energy consumption at a particular utilization is an excellent key performance indicator for comparing different heat treatment installations and processes. Care must be taken to ensure that the utilization based on the maximum operating capacity is factored in and normalization is carried out on the values from any factory before comparisons, as utilization is a significant factor. The utilization is complex as there can be differences between the maximum design and operating capacity based on the current product mix being run in the process. Another difference is the maximum calendar hours and maximum scheduled hours. The maximum operating capacity and calendar hours should always be used to calculate utilization to ensure comparative results across different factories.

Case carburizing, location B has been shown to consume more energy than through hardening location A, while surface induction hardening, location C consumes the least. Surface induction hardening has also been shown to be less dependent on utilization and more energy efficient regarding energy losses. This opens up possibilities of switching between heat treatment processes if one consumes less energy and can still achieve the same material properties and client applications.

The results of this study have also shown that the values of one heat treatment process can vary from location to location; hence the detailed guideline and methodology prepared in this report will help to carry out further studies in all factories across SKF. Case carburizing, location B has the highest environmental impact, and this is due to the electricity mix. Hence the future availability of renewable energy should be considered in any location or factory before switching from gas to electricity.

6.1. Future Work

Based on the results and conclusion of this study, the following future work should be carried out in SKF to ensure the results of this study do not just end up on the shelf but are used to implement long-lasting changes to how things are done in SKF and contribute value to SKF.

1. Additional data collection for more heat treatment installations should be carried out in different factories across SKF to verify comparing the different heat treatment technologies. This can be done at some factories and doesn't require continuous monitoring to carry this out.

2. Utilization should be further evaluated across different factories in SKF as it has great potential to improve energy performance. This will provide a better understanding of the current utilization of different factories based on the current product mix and identify installations where utilization can be improved.

3. Continuous energy mapping should be done on all factories across SKF. Only three factories have been studied in this work, but SKF has over 140 factories worldwide. Energy mapping should become a tradition and part of the everyday culture at all factories across SKF to ensure continuous energy monitoring and improvements in

investment decision-making. The methodology and guidelines outlined in this report serve as the bedrock for this future work.

4. Energy metering should be carried out across factories in SKF. Energy mapping will not be possible if there is no measurement of consumption. Many factories have poor measurement and reporting levels, which should be changed. An energy metering section has been prepared in this work as a bedrock to implement these measurement meters across all factories in SKF.

5. The data collection and energy mapping process for continuous monitoring should be digitalized. This should be done in coordination with the Future factory team. The heat treatment process's current utilization and energy consumption should be monitored online and transmitted to a screen where the operators can see it and adjust the production process based on that information.

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