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1. Introduction

Industrial energy efficiency is a key component in the transition of the economy towards increased sustainability. For an industrial company, there are four means to reduce energy costs: implementing energy-efficient technologies, energy carrier conversion, load management, and more energy-efficient behaviour. The European end-use energy efficiency and energy services directive promotes, among other things, the removal of existing market barriers and imperfections that impede the efficient end use of energy [1]. Energy audits provide an important tool in reducing barriers to energy efficiency [2]. Furthermore, an initial, well-structured energy audit is the first important step in a successful in-house energy management program in industry [3].

From the global perspective, industrial energy efficiency is one of the most important means of reducing the threat of increased global warming [4] as the industry accounts for about 80 percent of the world's annual coal consumption, 40 percent of the world's electricity use, 35 percent of the world's natural gas consumption, and around 10 percent of global oil consumption [5]. Of great importance are thus different means which promote energy efficiency for the industrial sector. In Europe, growing concern for increased global warming has led to the implementation of a number of policy instruments such as the EU Emission Trading Scheme (ETS) and the European Energy End-Use Efficiency and Energy Services Directive (ESD). From the industry's perspective, supply side policy instruments like the EU ETS will most likely result in higher European energy prices which will stress the industry to take actions toward increased energy efficiency. On the other hand, this may lead to competitive disadvantages compared to industries outside the EU [6].

The role and importance of energy audits varies from country to country. In a comparing study of factors influencing energy efficiency in the German and Colombian manufacturing industries [7], firms and associations were asked about their view on energy audits. Among the German respondents 57 percent states that voluntary audits is an important factor influencing the energy efficiency in their country, while 61 percent of the Colombian respondents states that voluntary audits is an important or very important factor. When they were asked about their own measures and actions, 71 percent of the German respondents and 54 percent of the Colombian respondents stated that they would consider energy audits to increase energy efficiency performance.

This audit method was developed in Sweden, in the Swedish manufacturing industry context. Evaluations of conducted energy audits in small and medium-sized manufacturing companies shows that the calculated technical potential for increasing energy efficiency performance varies from 16-40% of the total energy use. For electricity the calculated potential is up to 60% [8]. If the suggested measures are implemented and if the potential is reached or not depends on the barriers and driving forces for energy efficiency. The energy price can play an important role. For Swedish industry, energy prices have risen significantly in recent years. Between 2000 and 2006 electricity prices in Swedish industry almost doubled and oil prices rose by about 70 percent [9,10]. This trend has not declined. In January, 2010, prices on the Nordic electricity spot market arose to some 130 Euro per MWh. The electricity price increases were partly due to the deregulation of the European electricity markets as the deregulation has caused the national markets to converge and Sweden has for a long time enjoyed one of the lowest electricity prices in Europe [11]. While the oil price increases may not create competitive disadvantages for Swedish industry, the electricity price increases most likely will, as this is particularly related to the Swedish industry and the fact that the previously low electricity prices have resulted in a higher use of electricity in many Swedish industrial sectors compared to their European competitors.

The methodology described is primarily for a technical energy audit with the aim to make the energy use more efficient and sustainable. In the audit, organizational issues and the surrounding society are regarded mainly as means to reach the goal, and are important driving forces to implement changes.

1.1. Classification of energy audits

Energy audit models can be described in terms of the scope, thoroughness and aim of the audit [12]. The method presented in this chapter normally is used with a broad scope, covering the entire studied site. The thoroughness can vary from rough comb to fine comb and often the thoroughness varies between different unit processes in the same audit. As a top-down approach is used, the auditor always starts with a broad scope and a rough comb. As the audit progresses and the key areas are pointed out, the data collection and analysis become more detailed. Lytras [12] also describes the aim of an energy audit as either to point out general energy saving areas or to propose specific energy saving measures. With the method described in this chapter, pointing out the general energy saving areas is one way to identify specific measures and prioritize them.

Energy audits can also be described with the classification of energy audits from ASHRAE [13]. This classification involves three levels, defined in reference [14], and is similar to the audit procedure presented in reference [15]. The three levels presented in [13] are Level I (Walk-through assessment), Level II (Energy survey and analysis), and Level III (Detailed analysis of capital-intensive modifications).

The Level I walk-through assessment involves an assessment of the energy cost and efficiency by analyzing energy bills and a brief survey of the site. This first-level assessment targets low- or no-cost measures and presents a listing of capital improvements that need to be studied further. Level II, energy survey and analysis, includes a more detailed survey and analysis of the plant studied [13]. This is usually done by some form of detailed breakdown of energy use, either in activities and energy carriers or, as in this chapter, in unit processes. An energy audit with the method described in this chapter always involves the assessment at Level I and Level II.

1.2. Unit processes

A unit process is defined by the energy service to be performed and industrial processes may thus be divided into two categories of unit processes:

- Production processes – the processes needed to manufacture the products.
- Support processes – the processes needed to support the production processes but not needed for production.

	Disintegrating		Administration
	Disjointing		Cooling
	Mixing		Lighting
	Jointing		Compressed Air
	Coating		Ventilation
Production processes	Moulding	Support processes	Pumping
	Heating		Tap water heating
	Melting		Internal Transport
	Drying		Space Heating
	Cooling/Freezing		Steam
	Packing		

Table 1. The unit processes used at Linköping University, divided into production and support processes.

Unit processes are a way to divide the energy use of an industry or other businesses into smaller parts. The unit process perspective also enables one to question the methods used for different processes. Air flows in ventilation systems are sometimes high because the ventilation system

may be dimensioned both for ventilation and cooling. If you see that the device is taking care of two different processes you also see that there is a point in adjusting the flow depending on the cooling demand.

The concept is based on the objective of the industrial process, the mixing of materials, cooling or drying a product, the production of compressed air or to carry goods, etc. Unit processes are considered to be the smallest components within an industrial energy system. Unit processes are general for all industries, thus providing opportunities for comparisons of a given unit process, such as forming, between different industries. Using the unit processes to represent the “building blocks” of energy use also enables modelling, e.g. simulation or optimization modelling of industrial energy use. For example, see [16].

2. Methodology

This section describes one method to survey and analyze the energy use of an industry. The industrial energy audit may be divided into three main parts: the survey, the analysis and the proposed measures. The expected result of the energy audit is a number of measures that will increase the energy efficiency, switch from non-renewable to renewable sources and decrease the energy use of the company or in the energy system as a whole. The result is normally presented in a report.

In the three parts of the audit you have different tasks:

Energy survey – What do we have?

- Define the system boundary.
- Identify unit processes.
- Quantify energy supply.
- Allocate energy use to different unit processes.

Energy analysis – How “bad” is the utilization of the supplied energy? Where does it go wrong? How far can we reach?

- Identify both system errors and detail problems.
- Identify idling power and energy.
- Identify technologies that are far from BAT (Best Available Technology).
- Identify mismatching energy quality, where high quality energy is used for non-demanding purposes, for example, electricity for low temperature heating.
- Identifying barriers and driving forces.
- Sum up the potential for energy efficiency and conversion for the system as a whole.

Suggested measures – What can we do about it?

- Identify possible solutions.
- Calculate the impact of the solutions and analyze them.
- Calculate the economic impact.

2.1. Top-down approach and iterative method

The energy audit is basically a project with the aim to suggest energy efficiency and conversion measures. The basic method is the project method, but the actual workflow does not follow the straight project line from survey to measures. In practice you will start analyzing problems and identifying solutions as soon as you start collecting information for the survey. The analysis and ideas for measures will also affect the need for data collection. Ideally, the method may be described as an iterative process, as shown in Figure 1, where the iterations stop when you have enough data to suggest relevant measures.

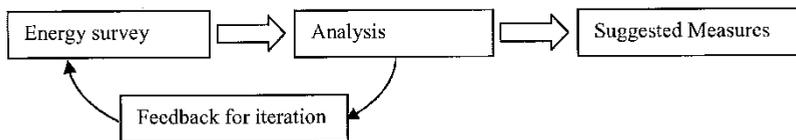


Figure 1. Schematic workflow for an industrial energy audit.

The iterative method is combined with a top-down approach. In this case, it means that the studied object (organisation, business or site) is initially considered as a unit, with its streams of energy and materials (Figure 2). The total use of different kinds of purchased energy is quantified. The material use and the products may be described but not necessarily quantified.

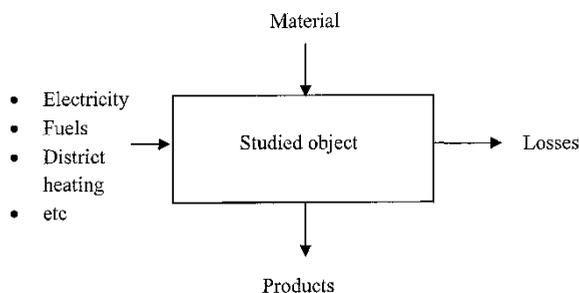


Figure 2. The top level of the top-down perspective for an energy audit.

The next step is to describe the unit processes and analyse them in terms of energy use (Figure 3). The first overview of the energy use makes it possible to relatively quickly identify key areas where additional resources are needed for measurements and analysis [17].

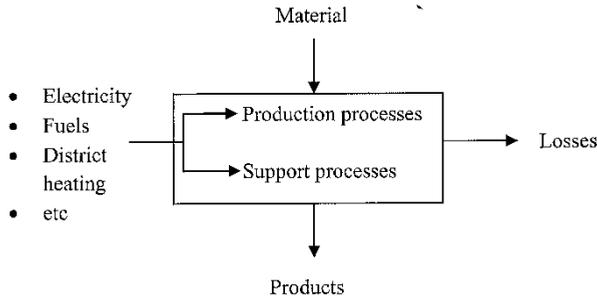


Figure 3. The second level of the top-down perspective for an energy audit means going into more detail concerning unit processes.

The next possible level is to find the data that enables you to allocate the energy use to the relevant unit processes. Which processes are relevant depends on the purpose of the audit. The top-down approach can continue further down, to individual components if necessary. How much detail the investigation will involve depends on the purpose of the audit, the possibility to acquire data, the complexity of the suggested measures, the timeframe for the audit, etc.

The point of starting from the top and working your way down is that the detailed information should be provided where the auditor thinks that it is needed, but not necessarily everywhere. The level of detail will vary between different unit processes. Sometimes the energy of all unit processes in a production line is summarized under the heading of Production Processes. It can be done for practical reasons, such as when a machine with only one energy supply handles multiple unit processes, or because the audit is delimited to focus only on support processes.

2.2. Typical process for an audit

In practice the activity schedule for a project can look like this:

Week 1: Start meeting with the company for project start and start collecting information. Wait for data from the company. Describe the unit processes. Collect basic data, like annual energy statistics (from energy supplier) and if available figures from sub-metering at the plant, as well as technical drawings. Finally, analyze the collected material. For example, where may the largest energy efficiency potentials be located? Where can we probably measure what we want?

Week 2: First visit on site – identify energy supply to different unit processes, collect data, measure, put loggers in place, count equipment.

Analyse data from visit. Detailed data is now available, but a top-down perspective is still applied, e.g. where may the largest energy efficiency potentials be located, which unit processes are most promising and in which areas do we need more data or knowledge?

Week 3: Second visit on site – remove loggers, additional instantaneous measurements. Analyse data from loggers. Completing the survey.

Week 4: Calculate the energy efficiency potential of the measures. Find suppliers of equipment needed for the measures, and wait for data from them. Complete the report.

Week 5: Third visit on site – present the results. Validate the proposed measures with the company staff. Some optimal (in terms of calculation) energy efficiency measures may be switched to second or even third-best choice after discussion with company staff.

Please note that this is a schematic example of how an energy audit could be carried out. The same method can be applied on different scales. A quick Level I audit at a small facility (i.e., five employees and 500 MWh electricity per year) can be finished in two weeks and less than 30 working hours. It would be fully possible to spend several months on a larger and more complex object (i.e., >5 buildings, many energy supplies, several production lines) which demands a more thorough audit and detailed measures.

2.3. Defining the object and the system boundaries

The object for the audit and its system boundaries have to be defined. As it is an energy audit, you will study energy flows, but the focus may be limited. The focus can be on decreasing a supply, e.g. electricity, fossil fuels or purchased energy, or on a part of the object, e.g. the building envelope or support processes only. The system boundaries can be an organisation or a part of an organisation, a building or a physical area with more than one organisation. The perspective can also be broader, for example, taking management or economic aspects or embedded energy into account.

As the method is iterative, you might have to narrow or widen the system boundary, depending on the limitations and possibilities you find on the way. One example is if the organisation you study owns the building where they work, but you discover that they also have a tenant working in a smaller part of the building. Instead of trying to calculate how much energy the tenant uses, the system border can be redefined to cover the tenant too.

Another example is when there is an existing or possible symbiosis between two neighbouring businesses. In this case the system is growing from one to two companies. A very common case is that the audited business is renting the building they work in. In this case you have the choice to exclude the building from the audit, but you will most probably find more and better efficiency measures by treating the building and the business as one system, with the business owner and the landlord as two participants.

2.4. Energy survey and analysis – Introduction

With the energy survey you will be able to create a power balance and an energy balance with the incoming energy allocated to different unit processes. To be able to suggest energy efficiency and conversion measures you also need to understand how the processes work, at least when it comes to energy use. The aim of the energy survey is not necessarily to create a very detailed map of the energy use, but to find the potential for energy efficiency measures and potential conversion to renewable energy sources.

By starting with an overview of the energy system and using a top-down approach it is possible to find the potential changes at the structural level, and avoid being limited to details. By combining the top-down approach with an iterative method for the data collection, it is possible to go further into details without getting overwhelmed with detailed data that is not really needed.

There are different ways to get the data you need. Provided that the top-down perspective is used, you don't have to collect all possible data about every device. The data collection begins with the most accessible data at the most general level which is considered useful by the auditor (using a top-down approach). The analysis starts with analyzing that initial data. The analysis will probably raise questions, which are used to guide the coming data collection procedures.

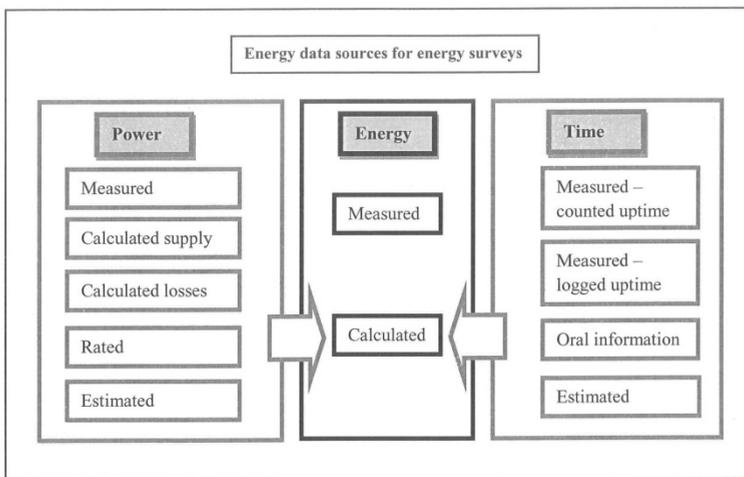


Figure 4. Some possible energy data sources for energy surveys.

At some level you have to stop the data collection despite not having all the answers. The limit is often the time reserved for the project, but it can also be the possibility to measure, practical obstacles to changing a process or the lack of historical data. It is often necessary (and possible) to use data from a more aggregated level, together with some analysis, calculations and assumptions. The data collection procedure could be carried out in the following way:

- Step 1: Gather statistics: electricity, district heating, fuel, water, production rate, etc. Gather drawings and plans.
- Step 2: Visit the company during operating hours.
- Step 3: Visit the company during non-operating hours.
- Step 4: Create a power balance, energy balance and allocate energy use.

To complete the audit you need to take two more steps:

- Step 5: Create an energy balance after adjustments (showing the impact of the suggested measures).
- Step 6: Confirmation of audit results.

The main purpose of the data collection is to give you basic data to identify relevant unit processes, to create a power balance and energy balance for these processes. Another purpose is to get enough data to be able to suggest adequate measures for energy efficiency and conversion. The origin and quality of information can vary greatly. Focusing solely on the energy data, the potential data sources can be categorized as shown in Figure 4.

2.5. Step 1: Gather statistics, drawing and plans

Before you have even visited the object of your survey, you can review the statistics concerning the use of electricity, district heating, fuel and water. You might also have supply of other media, such as steam or compressed air. Also try to get statistics on (or estimate) the production rate during the same period. Production data will enable you to estimate the specific energy use, for example in terms of kWh per produced unit, per hours worked or per tonne of raw material used. This can be useful both for allocating the energy and for calculating the result of suggested measures.

You can also ask the staff what activities are going on at the studied site, to get a picture of the unit processes and energy flow you should look for when you get there.

2.5.1. Electricity supply data

The electricity sales company and the electric grid owner are sources for the electricity supply data you need. It is good to have as much detailed data as you can when it comes to electricity use. The grid owner can provide consumption data with hour by hour resolution to their customers (at least in Sweden). If the object of the survey is small or if it has small sub-meters, there might be a problem to get hour by hour data. Energy data for a whole year, regardless of the time resolution, is recommended for analyzing the dependence on outdoor temperature.

Detailed data on the total electricity use during the period for which you are mapping the unit processes is also important. Sometimes you can use the customer ID number and a PIN code to get the hour by hour use from the supplier via the Internet. In that case it is easy to also download data for the period when you make your own electrical measurements. Another option is to log the total incoming electricity during the same period.

From the invoices you can get information on prices, power use, reactive power, etc. The invoice from January typically contains a summary of the energy use for the last year.

To some extent it is possible to analyze the data before visiting the company. You can compare the energy use graphs for production hours during different seasons to find electrical heating and cooling loads. You can also compare idling energy losses in different seasons and analyze total energy use, power peaks, reactive power, etc.

2.5.2. District heating supply data

Sometimes it is possible to get historical data on the energy used for district heating with hour by hour resolution, but often you have to be satisfied with the amount of heat used per month. Sometimes you can use the customer number and a PIN code to get data from the supplier via the Internet. If you ask for the service in advance, the supplier might be able to give you hour by hour resolution data for the time of the audit.

2.5.3. Fuel supply data

Fuels such as oil, wood pellets or wood chips are mostly bought in batches. To be able to calculate how much fuel was used in the past, you need to know how much fuel there was to start with, the purchased amount and how much is left. If the needed data is not available you might be able to estimate the fuel use by calculating the heat losses.

2.5.4. Other energy supplies

There are also other possible energy supplies, such as steam, compressed air, liquid nitrogen for cooling, welding gas, etc. As long as someone is charging for the supply you might be able to get some historical data, but it is not always the case. It is a good idea to look for informal energy flows: Two neighbouring companies can share the same district heating supply, air handling unit or air compressor, there might be solar heating for hot tap water or the company uses residues, such as wood chips, from the neighbour for heating. Energy supply not considered as energy can sometimes turn out to be important. Liquid nitrogen for cooling and welding gas for oxy-fuel welding are two examples.

2.5.5. Miscellaneous background data

Some other data that might be useful include:

- Water supply data, to be able to calculate the hot water use.
- Drawings of the building, floor plans.
- Drawing of the electricity supply systems.
- Drawing of other energy supply systems, for example hot water pipes, compressed air pipes
- Information on the ventilation: Drawings of ventilation ducts, number of air handling units and air flows.
- Information on time schedules for production processes, ventilation or lighting.
- Energy efficiency measures that are already taken.

Drawings can guide you to where in the system or in the building measurements can be made and what information to ask for. The drawings can also give you information that you can use directly. Air flows can be noted on ventilation drawings. Rated power for electric equipment, like motors and heaters, can be noted on detailed electrical drawings at the distribution board

level. When data such as documentation from a drawing is used, it is a good idea to make sure the data is up to date, by asking the staff about changes or by using measurements to validate.

2.6. Step 2: Visiting the company to collect data

By visiting the company during production hours, you can find out how the processes work, examine the design and function of systems and equipment, validate the descriptions, drawings and layouts you already have (for example of building and air handling units) and fill in the gaps where you have no data at all. When you visit the company you have the opportunity to:

- Speak to the key persons in different areas, operational and maintenance staff.
- Note the uptime and downtime for different devices, by registering how the processes work and by asking the staff.
- Inspect the building envelope and the space heating system.
- Review the procedures for service and maintenance.
- Go through all the unit processes systematically.
- Assess the function and condition of the equipment.
- Make an inventory of installed power, for example for motors, light sources and other devices.
- Measure the power used by a selection of important equipment. It might be the most energy demanding devices or any equipment you identify as critical to be able to divide the energy flow into different unit processes.
- Look for control systems (for the ventilation or for a production line). If there are any, you can try to find out if they are used and how they work. From the control systems for example you might get timetables with operation hours or logged data on production rate.
- Count the number of devices (for example light sources or computers) to make calculations later, using templates.

By speaking to key persons you can find out which unit processes are used at the company, uptime and downtime for different devices, operating hours for the factory and more. The key persons can be found among energy managers, production managers, caretakers, machine operators or others, depending on the organization. A caretaker or in-house electrician is a good guide when you want to find the devices you want to examine and the switchgear where to measure electricity. The production manager can inform you about the different production processes and their operating times.

Data on electricity use is mostly in focus. Data on airflows, water flows, pressure, temperature and size is often useful. Often you find set values and statistical data from sources like plans, technical documentation or monitoring systems. The main purpose of the survey is to get an overview - it is not necessary to measure all parameters during the survey to create the power

and energy balance. Still, sometimes measuring is the easiest solution and more accurate and precise measurements might be necessary to be able to predict the results of proposed efficiency or conversion measures.

As the audit is a temporary project, the audit itself is not an incentive to install permanent meters. If sensors, for example, for power, current, air flow, pressure or temperature are already installed and relevant data already logged or is possible to log, of course they should be used for the audit.

Sometimes you can also log the output signal directly from the control system with a voltage or current logger, depending on the type of signal, mostly 0-10 V or 4-20 mA. The logged information can be used directly as indicator of the uptime of equipment, e.g., an air handling unit. For further calculations you also need to know what real condition the signal represents and adapt your logged values to that.

2.6.1. Electric power measurements

The data from the energy supply company is not sufficient for allocating energy use to all different unit processes. Internal energy measurements from the studied facility can sometimes be found, especially for well-monitored core production processes. Still you will probably have to measure the electric power used by a selection of important equipment to be able to allocate the energy use and construct the power and energy balance. To make electrical measurements is very often the main activity when the studied object is visited.

Apart from measuring the energy use directly with permanently installed meters, there are different ways to measure the power or current for electric equipment to help you calculate the energy use. To calculate the energy use from electrical measurements you will need the active power. When visiting the company, it is preferable to measure the active power directly with a wattmeter. Measuring the current and voltage separately will enable you to calculate the apparent power, which cannot be used directly for energy calculations. The apparent power is only useful when the power factor is known from previous measurements or from technical documentation. Rated power for different electric equipment can be used to some extent, but normally it should not be used for the calculations. Rather, it is more appropriate to obtain the power or current and power factor from measurements.

A short visit to the studied site will not provide sufficient information to allocate energy use. To see changes in power use, a combination of current transducers (AC current clamps) and digital recorders (data loggers) can be used. A useful method is to let the data loggers record the current for one week. This will give you information about changes in usage patterns during working hours as well as nights and weekends.

The use of electric energy is very often in focus in the energy audits conducted by Linköping University. Methods and material for electric measurements and evaluation of data are also developed for energy audit purposes. Examples are shown in section 3. Practical examples - Measurements and analysis.

2.6.2. Air flow measurements

Air flow measurements can be used to calculate the ventilation heat losses, and also to roughly estimate the electric power used for the fan motors. On the other hand, the electric power used for the fan motor can also give you an idea about the air flow, and the electricity is often easier to measure. Sometimes the optimal way to find out the operating time for a machine or the working hours in a building is to log the ventilation air flow or temperature or the electricity used by the fan motor.

2.6.3. Temperature measurements

Temperature data are particularly useful for calculating the energy use of the unit processes Space Heating and Cooling and Ventilation. Temperature measurements can be used to calculate the efficiency of heat exchangers for AHUs. To calculate the heat losses, the exhaust air temperature is crucial, but seldom registered by the monitoring system and even more seldom logged. To use standard values for efficiency of the heat exchanger is a useful shortcut.

Temperature logging can be used to identify operating time for equipment. A temperature probe can be attached directly to the surface of a machine or in an air flow or other medium connected to the studied equipment.

2.6.4. Size measurements

To analyze the heat losses from a building the size of the building and the properties of the building materials must be known. Measuring the size of windows and doorways, thickness of walls and height of ceilings is often part of the survey. For air flow measurements in ventilation ducts, the size of the duct must be known.

2.6.5. Make an inventory of installed load and operating time

A fast and effective means is to count motors, light sources, computers and other devices and note their rated power. You find the rated power for motors and other devices on name plates or in technical documentation. Also note the rated $\cos \varphi$ for the motors, for future loggings of electricity - if you don't get the opportunity to measure the true power factor or $\cos \varphi$, at least you have an idea of the figure. Even though the scientific literature provides examples of this approach, see e.g. [18], it is strongly recommended that the power factor is obtained by measurements. This is due to the wide variation of power factor which occurs from different applications.

To get the energy use for computers, copiers, servers and printers, you can get a good enough estimate by counting the number of devices and calculating the power and energy used. You probably have to use templates and estimates for these.

To get the power and energy for light sources, a good method is to count the number of different light sources and note the different rated power, printed on the light source, on the package or in technical documentation. This method works as long as the lighting is controlled by an on/off switch only. When you have discharge lamps, such as light strips, you have to

add the power used by the ballast (control gear). Make sure to find out if it is a magnetic ballast (very common, always in older installations but still used today) or the more modern electronic ballast. Magnetic and electronic ballast differ in power use. For light strips with the common magnetic ballast it means multiplying the rated power by 1,2 and for the more modern electronic ballast it means multiplying by 1,1.

The uptime for the lighting might be hard to find out. You can simply ask the staff, log the light or temperature at selected light sources or log current used for lighting to be able to see the true uptime and downtime.

2.7. Step 3: Visit the company during non-production hours

This step is performed to find out what equipment is operating during non-production hours and find out if it must be operating. You might find support processes - lights, air handling units, compressors - being switched on though there is nothing to support, but also production processes in idle or stand-by mode.

Eyes and ears are useful to find equipment running during non-production hours. The measurement methods used are the same as during production hours, but the focus may be on other processes.

2.8. Step 4: Create a power balance, energy balance and allocate energy use

When you start constructing the energy balance, you will have data with different quality – detailed production data, estimated operating time, rated data, etc. You will have data with different time spans and time resolutions - statistical data for a whole year, one week measurements, instantaneous measurements, etc. The data will also describe different parts of the energy flow - sometimes the energy supply, sometimes the usage and sometimes the energy loss. In Figure 5, an example of an energy balance is presented.

Below some different common cases related to allocating energy use are outlined.

Case 1 - All the supplied energy is allocated to one specific unit process. Sometimes you can find this phenomenon for support processes, such as fuels for internal transport or district heating for space heating. Some of the supplied energy can also be very specific for a certain production process, such as gas for welding or liquid nitrogen for cooling.

Case 2 - Almost all of the supplied energy is allocated to one specific unit process – all you have to do is to take something away. In Figure 5 this is the case for Space Heating and Hot Tap Water which are the only processes supplied by the oil boiler.

This can often be the case when you use a hot water system for both production and Space Heating and Cooling. One example is a district heating hot water supply used for both a washing machine for surface treatment and for the indoor climate and space heating system. The space heating is mostly weather dependent and varies with the seasons. The energy use of the washing machine totally depends on the rate of production. Given that you have at least monthly data from the district heating supplier and that you know the production rate during the summer, when the heating system is mostly turned off, you can estimate the energy use

for the washing. Then you can compare the energy use during the summer and winter, subtract the energy use for washing and assume the rest to be heat for space heating and air handling.

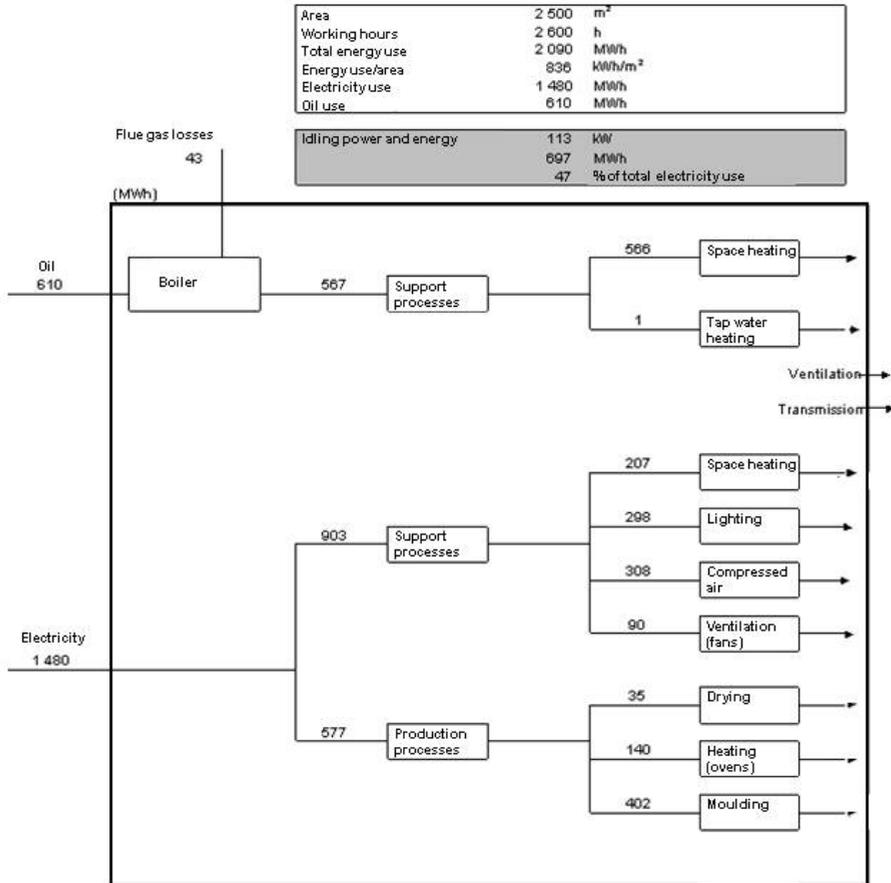


Figure 5. Energy balance for an audited plant [19].

Case 3 - Many different unit processes have the same supply, but at least some of them are running in a predictable way. This is often the case when it comes to electricity, as seen in Figure 7. From the switchgear or the distribution board, where you often have the practical possibility to measure, electricity is supplied to many different processes. Typically you find all the processes in one part of the building mixed. Even if the distribution board is totally dominated by one production process, like a laser cutter, you might also find support processes for that production process, like a compressor and a chiller, attached to the same board. The energy use for the laser cutter itself will vary a lot, but if the chiller works constantly as soon as the cutter is on and the uptime of the

compressor already is measured for service reasons, you might be able to allocate the energy use by logging the total current to the distribution board.

If you have a common supply for even more processes, try to find the ones with constant power use, like light strips, or constant power use and programmed uptime, like air handling units with constant air volume and an autotimer.

Case 4 - A process has more than one energy supply. This is of course a common case. In a building with many air handling units, the units are all doing the same job – they are running the ventilation process. Even if there is a central remote control system for all air handling units, usually the energy use is not logged. The solution is to add up all the air handling units, accepting that your input data quality will range from rated power and estimated uptimes to detailed measurements.

You can also have one process with different energy carriers, e.g. a dryer consisting of an electric fan and a hot water heater. If you are not able to register everything, you might be able to use data from one of the carriers to calculate the uptime for the other. For example, the temperature of the heat exchanger can reveal if the fan is running or not.

You might also find two separate electricity supplies to the same unit process for safety reasons, i.e., two separate air compressors connected to two different switchgears to prevent stoppage. Of course you can have more than one supply to a single unit process for other reasons, for example if the electric distribution system has been supplemented because the process needs more electricity than the original switchgear was designed for.

2.9. Step 5: Creating an energy balance after adjustments (showing the impact of the suggested measures)

Depending on what kind of problems the auditor has found, different solutions are proposed. There are four principal means of reducing industrial energy costs as shown in Table 2.

Principal means of reducing industrial energy costs	Comment
Energy-efficient technologies	Improved efficiency among technologies using energy is one of the foremost and most common means of increasing energy efficiency in industry.
Load management	Reducing power costs by aiming to minimize the power loads is a common means for industry
Change energy carriers	Changing energy carriers, e.g. switching from oil to district heating is a means for industry to cut costs
Energy-efficient behavior	Energy-efficient behavior is a simple measure involving more efficient behavior among staff at the industry

Table 2. Four principal means of reducing industrial energy costs

It should be noted that the above table concerns energy costs. As regards reduced energy use, load management is not an energy-saving measure as it solely shifts the use of energy to times where it is more appropriate. Moreover, change of energy carrier may be a splendid way to reduce the use of non-renewable resources or energy costs. However, it may not lead to reduced energy use.

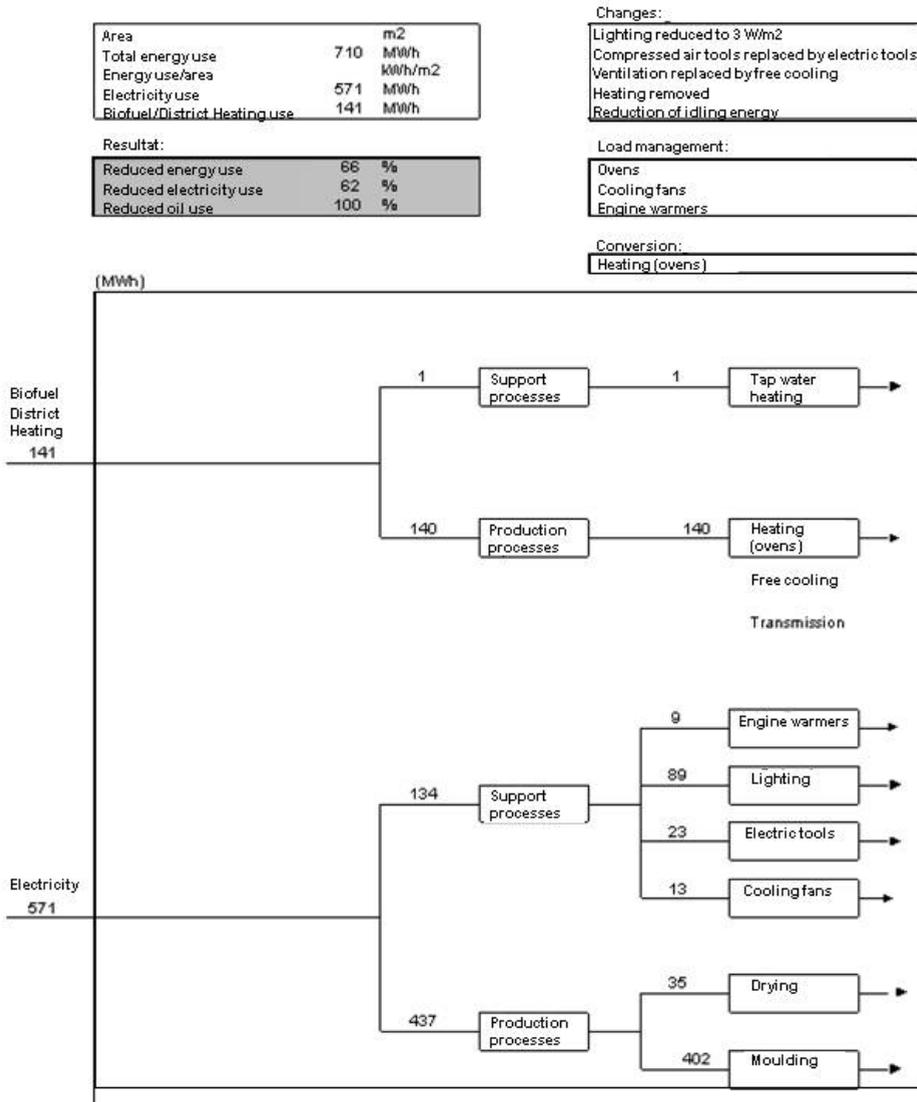


Figure 6. Energy balance after suggested adjustments [19].

When the impact of the proposed measures is calculated, a new balance is presented (Figure 6). The new balance can have two different purposes: It can show the potential for changes in the energy use or it can show the calculated impact of the measures. The potential for energy efficiency can be estimated with standard values for the best available technology. If the impact of the suggested measures is to be presented, more detailed technical and economical calculations are made.

2.10. Step 6: Confirmation of audit results

This part is of crucial importance, not least in regard to whether the energy audit results will, in fact, be accepted, and not discarded. Normally, a meeting is held with representatives from the industry concerned and the conductors of the audit about the proposed energy efficiency measures, and the analysis of the energy balance. In this step, the primary focus is on the proposed measures. For some processes, there are a number of different alternatives. This step enables the energy auditor and the industry representatives to discuss which measure is most suitable for the industry. Normally, this meeting is not with high level executives but is held with the maintenance manager or the energy controller.

3. Practical examples – Measurements and analysis

This section shows a few practical examples of measurements and analysis for energy audit purposes, focused on electricity. The building properties and heating and cooling systems are often important to examine in an energy audit. Air flow and temperature measurements are often needed. As there are fairly standardized methods for these tasks, they will not be further discussed in this chapter.

3.1. Allocation of electricity use – Measurement case description

In a typical measurement case we want to separate the electricity use for the unit processes air handling, lighting, compressed air, internal transports and packing. Instantaneous power measurements, current logging and rated power for equipment are used to allocate the electricity use.

Based on information from the staff at the industry, we know that the distribution board in Central Picking Stock is used for ventilation, lighting and electric tools for packing. The Central Garage distribution board is used for ventilation, lighting and a forklift charger. From the board Central Large Hall electricity for lighting, ventilation and packing equipment is distributed. Based on that information, and the drawings of the electricity distribution system in Figure 7, the plan for measurements may look like in Table 3.

The logging period is the same for all the current clamp meters, in this case seven days, to cover the variations in energy use in production hours as well as during the weekend. The range setting of the current clamp meters is to be appropriate for the load, but also depends

on the type of clamps and loggers available at the moment. In this case we have 500 A, 200 A and 20 A current clamp meters.

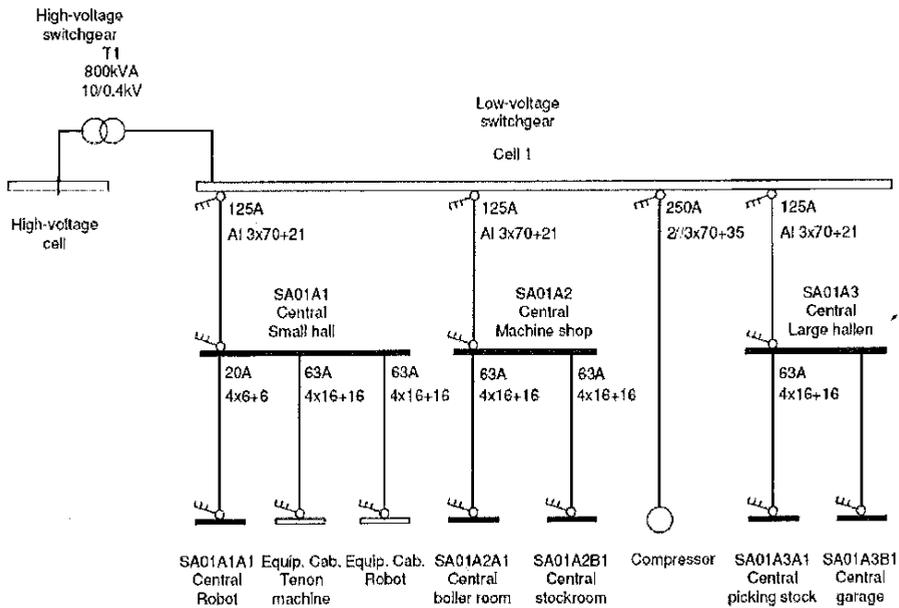


Figure 7. Example of a schematic drawing of an electricity distribution system.

The sampling interval for the current clamps can be changed depending on what we want to know. For the air compressor we may log more frequently, for example every five seconds, if we find that the compressor is switching mode very frequently, otherwise logging at 60-second intervals may be enough.

The purpose of the continuous measurement will also affect the logging interval. If the first visit gives us the impression that the compressed air system is an important part of the energy use, we may measure more carefully to have enough information to suggest detailed measures. The drawing of the electric distribution tells us that the fuse for the compressor is 250 A, but based on the information from the instantaneous measurements we plan to carry out, we might be able to replace the 500 A clamp with a 200 A clamp.

Unit process	Power data source	Time data source	Comments
Compressed air	Instantaneous measurements.	Logged data from current clamp 4.	Clamp 4 settings: range 200 or 500 A, sampling interval 5 to 60 s.
Lighting	Rated power, verified by instantaneous measurements.	Oral info on working hours. Verify with data from current clamp 1 and 2.	Clamp 1 settings: range 200 A, sampling interval 60 s. Clamp 2 settings: range 200 A, sampling interval 60 s.
Ventilation	Instantaneous measurements.	Air handling unit control system. Verify with data from current clamp 1 and 2.	
Internal transport	Rated power for forklift chargers combined with logged data from current clamp 3.	Logged data from current clamp 3.	Clamp 3 settings: range 20 A, sampling interval 60 s.
Packing	Rated power, instantaneous measurements.	Logged data from current clamp 1.	The residual energy is logged data from current clamp 1, minus clamp 2 and the energy for lighting and ventilation. The residual is equal to the energy for Packing.

Table 3. Example of plan for energy measurements to allocate electricity use to unit processes.

In this case we will have a measurement from a switchgear cabinet that covers several unit processes, for example lighting and forklift charging for a garage and picking stock, as shown in Figure 8. The data from clamp no. 1 in the switchgear must be complemented by simultaneous measurements from clamps 2 and 3 in the distribution board, where clamp 2 measures the total incoming current to the Central Garage board and clamp 3 measures the outgoing current to the forklift chargers.

Later, the data from clamp 2 in the Central Garage distribution board can be subtracted from clamp 1 in the switchgear to get a picture of the energy use in Central Picking Stock and Central Large Hall.

At the same time you have parallel measurements of the air compressor from clamp no 4. The clamp meter is placed in the switchgear, where the compressor has directly connected conductors, or in the compressor, depending on where you have the best access.

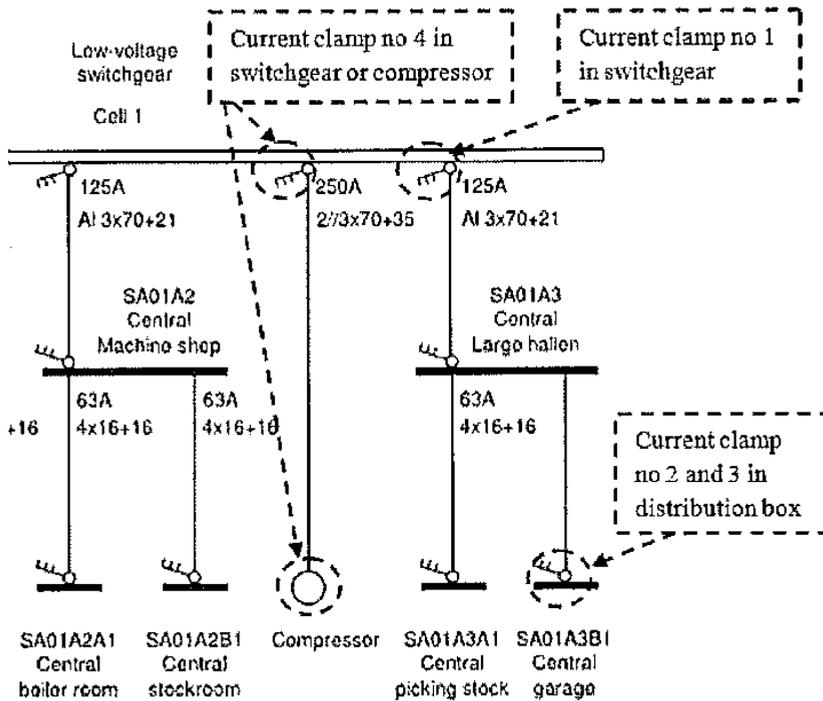


Figure 8. Part of a schematic drawing of an electricity distribution system, with locations for current clamps for simultaneous current measurement, to make it possible to subtract a part of the load from the total and separate electricity used for different unit processes.

3.2. Calculating the electricity use from logged data

Logged data can be used for calculating:

- Uptime.
- Average power for operating hours.
- Idling power.

In the example below the case is an hydraulic press, but the same procedure can be used for other equipment, for example to calculate the energy used to cover leakage in compressed air systems. With some more measurements and analysis, it can also be used for a complete building or workshop.

The idling energy, uptime and average power can be calculated in a few steps:

1. Measure the power factor at different loads.
2. Log the current.

3. Analyse the graph.
4. Convert the current to power.
5. Analyse the data again.

How to do this will be shown with measurements from a hydraulic machine for sheet metal processing.

3.2.1. Measure the power factor at different loads

The power factor is measured while the machine is running. The machine has two well-defined modes of operation – one when the metal sheets are actually shaped and one when the hydraulic motors are running without any load, i.e., idling.

Mode	Power (kW)	Power factor, λ
Active	< 250	0,82
Idling	48	0,38

Table 4. Measured power and power factor for a hydraulic press.

3.2.2. Log the current

The current is logged for about a week, to cover working days as well as the weekend. The original current logging data is presented in a graph (Figure 9).

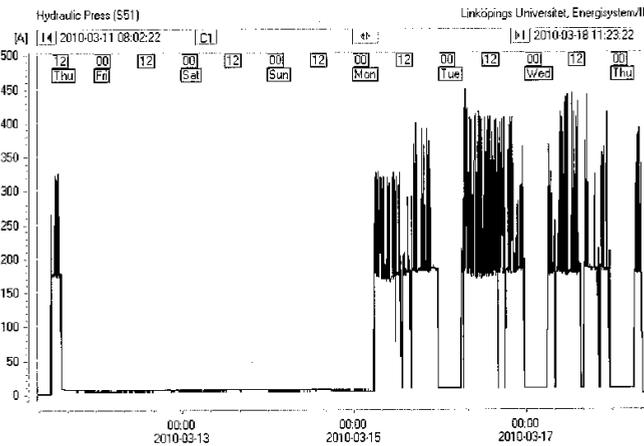


Figure 9. The current used by a hydraulic press during one week.

3.2.3. Analyse the graph

From the graph (Figure 9), it is clear that the machine is not used Friday to Sunday and for some hours during the nights. The machine is turned off during non-production hours. Nonetheless it has some idling power during the weekend and nights. The conclusion is that there are in fact three different modes to consider: active, idling and standby. The periods with zero current in the beginning and the end of the graph is the time before the logger was connected to the machine and after it was disconnected.

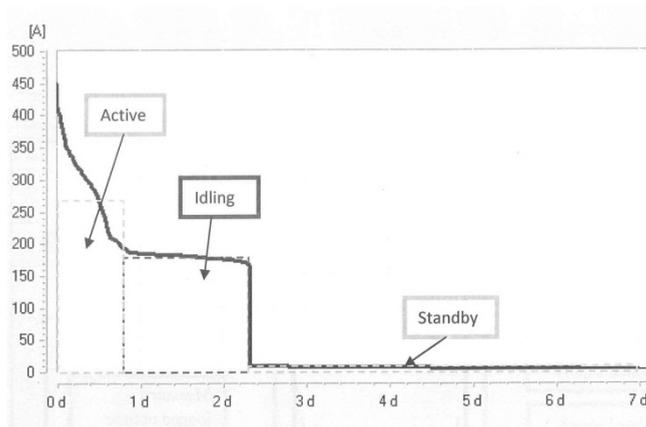


Figure 10. Duration diagram of the current used by a hydraulic press during almost one week (6,8 days). The active mode lasts for about 20 hours, the idling mode for about 1,5 day and the standby mode for about 4,5 days.

One way to analyse the graph is to create a duration diagram with the logged data, as in Figure 10. The duration diagram can be used to distinguish between the modes and to estimate the energy use for the different modes.

3.2.4. Convert the current to power

The power can roughly be estimated with the duration diagram together with the instantaneous measurements of the power factor.

Mode	Power factor, λ	Current (A)	Voltage (V)	Power (kW)	Duration (h)	Energy (kWh/week)
Active	0,82	270	230	150	20	3000
Idling	0,38	180	230	47	36	1700
Standby	?	5	230	3,5	108	400
SUM						5100

Table 5. Power and energy use for a hydraulic press during one week.

In this case a close calculation based on the raw data gave a similar result (5176 kWh) to the rough estimate, but that is mostly because the same assumptions were used. Changing the duration or average power just a little affects the result a lot. The power factor at partial load and at standby load is also unknown, which affects the accuracy of the calculations.

3.2.5. Analyse the data again

Together with information about the rate of production and the working hours, the annual energy use for this equipment can be calculated.

If this is a representative production week, the result can simply be multiplied by the number of working weeks per year. In this case it is not a typical week but information from the production manager tells us the working days are representative. The average power use during working hours can be calculated and multiplied by the number of working hours per year. In this case the rest of the year can be considered as standby time. In other cases equipment can be completely turned off during longer holidays.

Mode	Power, average (kW)	Duration (h/year)	Energy (MWh/year)
Working hours (active and idling mode)	84	3456	290
Standby	3,5	5304	19
SUM		8760	309

Table 6. Calculated annual energy use for a hydraulic press.

We know from previous calculations that about 35 percent of the energy use during working hours is really idling energy. That information is not needed for the allocation of the energy use to the right unit process, but it is important information for further analysis and to suggest measures. A closer look at the graph of the current used during a week also reveals that the machine sometimes is idling for more than one hour without producing (see Figure 9). One example is Monday before midnight, when it is idling for about two hours before it is at last turned off for the day. An automatic control system or changed routines for the operator can be used to switch to standby mode faster. The aim of the analysis was to be able to calculate the energy use, but on the way some possible measures were also found.

4. Concluding discussion

This chapter has presented the energy audit methodology being developed at the Division of Energy Systems at Linköping University for a period of more than 30 years. Despite extensive research and experience in the field – about 500 energy audits have been carried out based on this methodology - the energy audit methodology has not been explicitly outlined previously. This chapter may therefore still contain areas for improvements. This chapter has for example

not covered in depth the obvious risk of errors when collecting and analyzing the data and results in an energy audit. For practical reasons, measurements are normally carried out for one or two weeks. When setting up an energy balance, this period of time is normally assumed to be a representation of a “normal” week, and thus multiplied by a factor in order to gain an annual balance.

Moreover, it must also be mentioned that this methodology covers a Swedish and Scandinavian context, for which reason some material might be difficult to adapt in countries outside of Scandinavia. Finally, this chapter has not explicitly covered the in-depth calculations needed for various parts of an energy audit as there is no room for that in this context. The chapter does not cover all the various aspects of the energy audit methodology but rather gives the reader a basic introduction to the subject. After all, becoming a good energy auditor is not about reading a book, but is rather a continuous learning process where experience, not theory, is the major part of increasing skills.

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