DEA & EESD
Energy Partnership Programme
between Vietnam and Denmark

Technology guideline for heat recovery and heat pumps in Vietnamese industry

1
26’th of June 2024

Draft Final

Viegand
Maagøe

Resumé

This guideline for application of heat recovery and heat pumps in Vietnamese industry has been developed as a part of the cooperation between EESD and the Danish Energy Agency during 2024.

The purpose of the guideline is to provide a structured workflow for how such energy efficiency measures can be analysed and optimized, i.e. which data that should be collected, which assessments that should be made, which solutions that should be considered and how proposals for investments can be presented for the management in the companies.

The guideline is to be seen as a document that will undergo continued updates when new experiences are gathered from ongoing assessments in various Vietnamese industries. The guideline further has an important interface to other documents developed in the cooperation between EESD and the Danish Energy Agency, by example technology catalogues for efficiency of boiler and steam distribution systems.

The guideline has been prepared in close cooperation between The Danish Energy Agency and Viegand Maagøe with reviews performed by Vietnamese partners.

Indhold

ABOUT THIS GUIDELINE

During sites visits to industries in Vietnam, it has been experienced that significant energy saving potentials can be identified by a wide variety of measures.

One of the interesting areas to look into is heat recovery solutions and integration of heat pumps in the energy supply in the companies. Heat recovery can lead to significant energy savings in many different ways, by example:

- Recover heat from a process that need to be cooled to a process that needs to be heated
- Recover waste heat from combustion gas for direct heating of i.e. hot water
- Recover waste heat from exhaust air from a drying process, by preheating the incoming drying air.
- Recover waste heat from i.e. wastewater treatment plants and/or cooling condensers by heat pumps producing hot water up to 90 ºC
- Maintenance and repair of existing heat recovery systems
- Etc.

As such, heat recovery can be everything from simple solutions basically addressing maintenance procedures to complicated investment-projects necessitating careful planning- and design works.

This guideline is intended to be used by industrial managers, technology providers and energy efficiency experts for the purpose of optimizing the use of waste heat.

The guideline describes:

1. Fundamentals about heat recovery and heat pumps

2. Energy efficiency measures applying heat recovery and heat pumps

3. Approach to audits/screening, pre-feasibility and feasibility projects

The document includes a number of international cases for applying heat recovery and heat pump-solutions and makes reference to other documents developed under the Danish-Vietnamese cooperation on energy efficiency in industry.

1 Fundamentals of heat recovery and heat pumps

The application of heat recovery and heat pump-solutions cover a wide technical field with many practical questions to understand and assess when developing solutions to install.

This section aims at explaining the most fundamental questions to address and methodologies to apply when assessing energy saving potentials and technical opportunities for installing heat recovery solutions.

1.1 The rationale behind heat recovery solutions

Overall, a heat recovery solution aims at utilizing waste heat from one process ("warm") to heat another process ("cold") so that the energy demand to heat the latter using fossil fuels or biomass can be reduced thus saving operating costs and eventually also reduce CO2-emissions.

The principle of exchanging energy between a hot and a cold process is illustrated in figure 1 below.

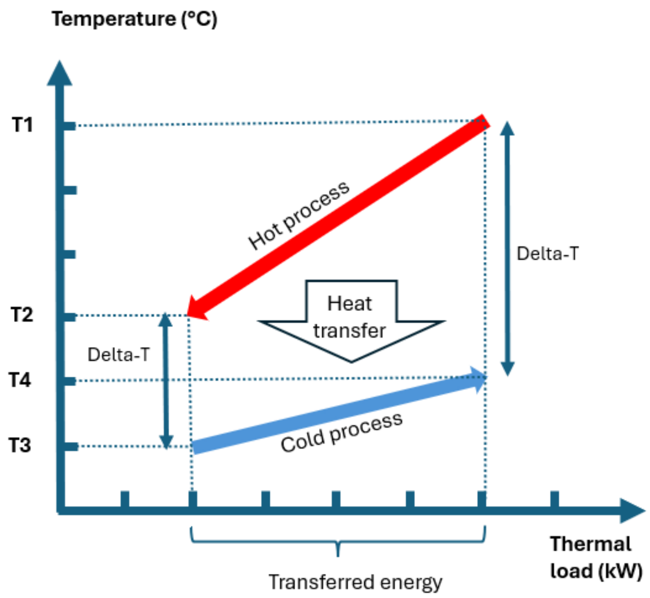


Figure 1. Simple principle of heat recovery between a "hot" process (source) and a "cold" process (sink)

The diagram illustrates the following principles of heat transfer:

- A "hot" process is cooled in a heat exchanger from the temperature T1 to T2

  The "hot" process is also called a "warm" process or a "source" and can be process streams that needs to be cooled or it can be a waste heat source (also called excess heat or "lose" streams[1]) where heat is vented to the surroundings.

- In the heat exchanger a "cold" process" is heated from the temperature T3 to T4 when receiving the heat from the "hot" process

  The "cold" process is also called a "sink" and will always be a heat demand covered via utility systems supplying steam, hot water or hot oil to the process.

---

[1] A "lose" stream is a "hot" stream that can be utilized if it contributes positively to the heat recovery system, but where cooling is not needed like needed for other "hot" streams.

- At each end of the heat exchanger a “delta-T” can be measured showing how efficient the heat exchanger exchanges energy between the two processes (the lower delta-T the better).

As such, the principle of heat recovery can appear simple, but the complexity increases significantly when the number of “hot” and “cold” streams increases.

In figure 2 below, a heat exchanger network (also called “HEN”) with 4 heat exchangers exchanging energy between 3 “hot” streams (red streams 1,2 and 3) and 4 “cold” steams (blue streams 4,5, 6 and 7) is illustrated.

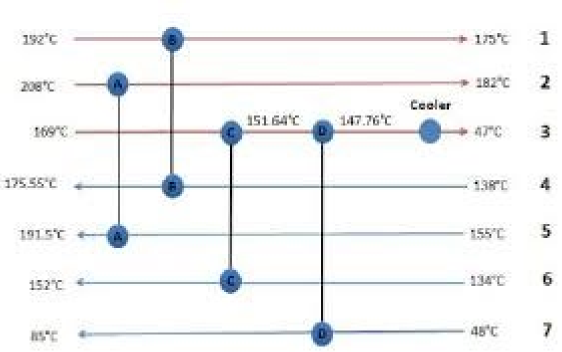


Figure 2. Example of complexity of design of heat exchanger networks.

Such a heat exchanger network will just from combinatorial reasons have several alternatives, which further is complicated to choose among because of different temperature profiles and differences in the heating/cooling capacity of the individual streams.

A common design failure in design of heat recovery solutions is to favor utilization of the “warmest” waste heat sources to heat the “coldest” heating demands. This is often favored because of simplicity and smaller size of heat exchanger installations, but from an energy efficiency perspective, such solutions might not be optimal because:

- “Warm” waste heat sources can be applied for heating of “medium” temperature heating demands…

- …thus allowing for utilizing “medium” temperature waste heat to heat “low” temperature demands

From such a consideration, the potential for utilization of waste heat in principle can be “doubled” thus reaching much higher levels of energy savings by installing more heat exchangers.

The picture gets even more complicated when heat pumps are also to be considered. Heat pumps will increase the temperature of “hot” streams (those with low temperatures) thus increasing the application potential for these significantly.

To deal with this complexity, a strong methodology approach to waste heat utilization is recommended, which is described further in the sections below.

1.2 Methodologies for assessment of heat recovery potentials

A systematic approach to assess heat recovery potentials shall follow the key activities described in the following sections.

1.2.1 Energy mapping ("Level-1"-mapping)

In order to be able to assess any heat recovery potentials an energy mapping of the facility is required. This is an important first step to develop a better understanding of energy usage and for developing a baseline for project development.

Overall, the energy mapping can be carried out by following the steps illustrated in Figure 3 below. The below approach has been developed with the aim of saving auditors time by carrying out the energy mapping as an iterative process, focusing on first getting a full overview of the energy demands before carrying out any detailed measurements. This enables the actual measurements to be prioritized on areas which have a significant energy demand These might be mapped simply and allowing a high uncertainty in the first iterations.

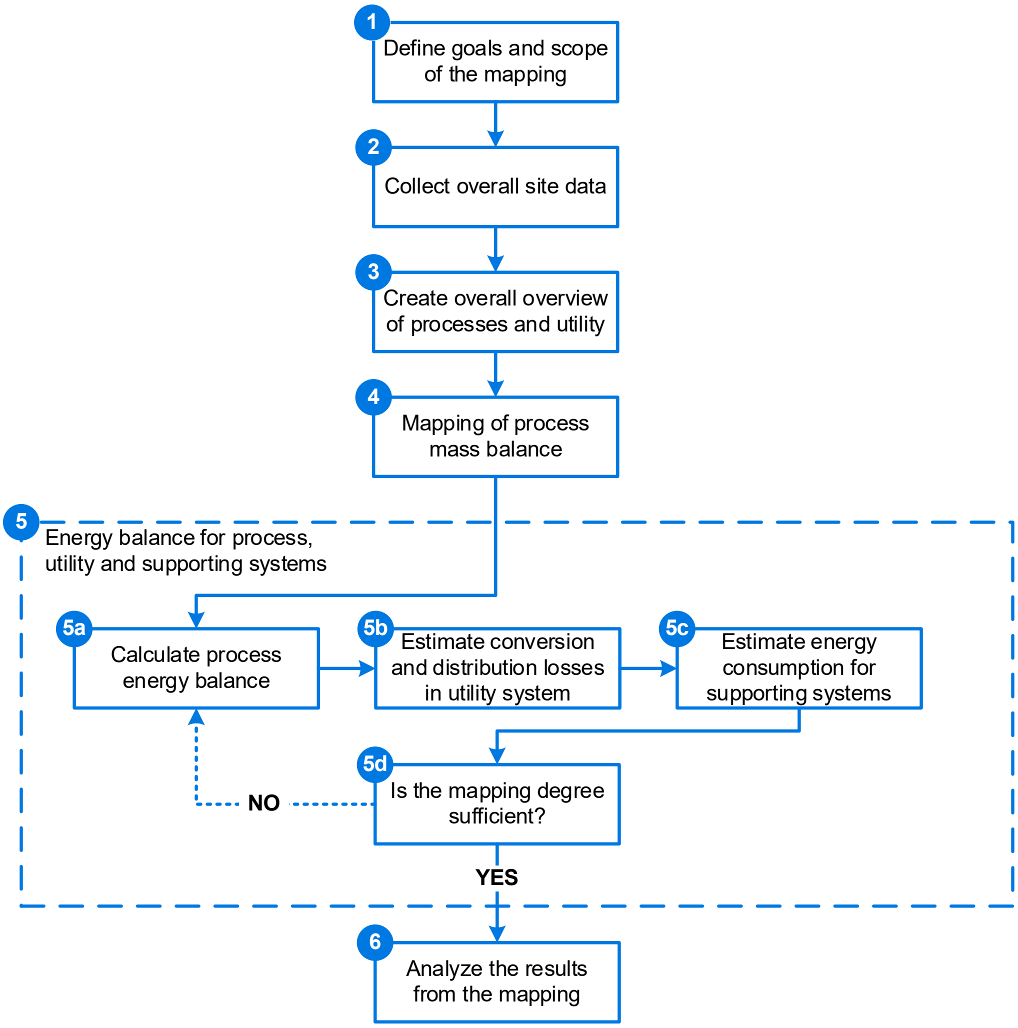


Figure 3. Flow chart of the stepwise energy mapping process

As a part of the DE3 program in Vietnam an energy mapping template has been developed in Excel with an accompanying user-guide. In the user-guide, each step of the mapping is described in greater detail. This guide can be seen in Appendix 1 and further includes an Excel-sheet allowing for important energy balances etc. to be calculated.

To easily get a full overview of the entire facility, pie charts and bar charts are made for each utility type at the site. As an example, an overview of the heating consumption in a facility is shown in figure 4 below (for the example in Appendix 1).

These plots provide a good overview of the distribution of heat consumption for the entire site and make it easy to identify the main energy consumers at the site. In the example these are only created on site level, but for larger sites they can also be created on a production line level or for individual workshops/sections, to have an even more detailed overview of where the energy is consumed. The overviews are created for each utility system at the site.

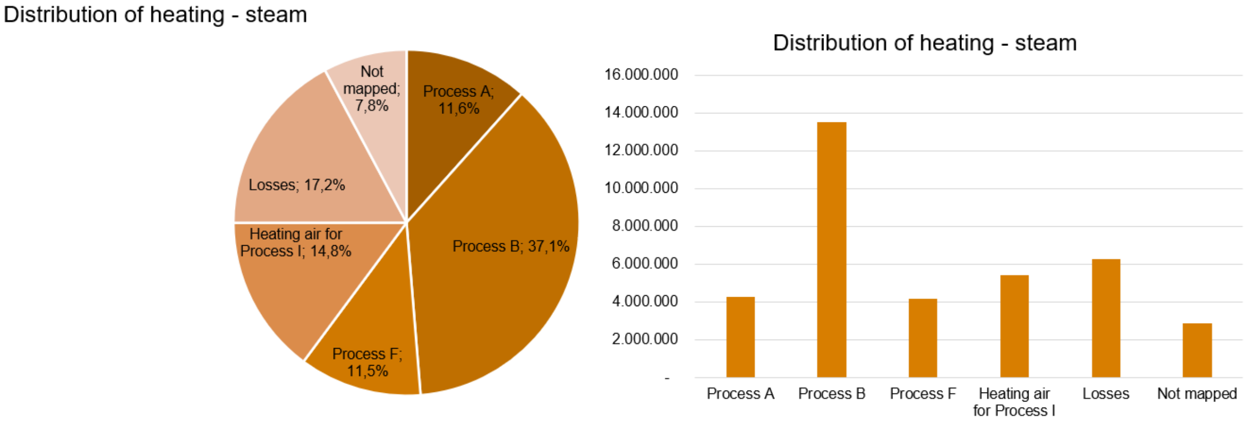


Figure 4. Example of mapping of heat demand consumption in an industrial company in an energy audit.

A similar overview of cooling demands should be established during the energy mapping. In traditional energy audits, cooling consumption is usually represented as an electricity usage, which is not enough when looking into heat recovery potentials. The individual cooling demands should be mapped similarly to figure 4 above.

The waste heat sources, such as heat lost with flue gas leaving the stack, can also be presented in the same way as the heating and cooling. The presentation of the waste heat can be in the form of the "lose" streams that could potentially be used to preheat other flows. By doing this a first overview of the waste heat recovery potential can be given.

1.2.2 "Level-2"-energy mapping

For companies with complex energy supply structures and multiple consumers of thermal energy (heating and cooling) a further assessment of design parameters for each consumer of cooling and heating must be carried out.

This is often the case for sectors like food & beverage, chemical industry and pharmaceuticals, where widespread heating and cooling distribution systems are seen in order to supply heating and cooling to many different areas of the facility.

These more complex systems most often also already have some existing heat recovery systems in place, and a full understanding these is necessary for optimizing the overall heat recovery at the site. The purpose of this next level of energy mapping is to establish a full overview of the production flow including heating demands, cooling demands and waste heat sources as the facility would look without any of existing heat recovery solutions in place - and based on the true temperatures of the processes.

The reasons that such a more detailed mapping is necessary are several:

- Existing heat recovery solutions might be in-effective due to fouling, poor maintenance or direct failures in control systems and operation
- Existing heat recovery systems can be designed wrongly or placed the wrong places in the processes thus blocking for new and more optimal heat recovery solutions

- It is necessary to understand the temperature requirements in the individual processes, where especially heating demands in processes < 100°C and cooling demands > 30°C are key targets for heat recovery solutions.

- It must be understood that often seen "high quality energy" is used for "low quality purposes" – by example steam is often used for heat of water and air at low temperatures (< 50°C) – or cold glycol is used for machine cooling at high temperatures (>50°C)

To map and understand these questions, a first step in the level-2 mapping is to establish detailed production flow diagrams identifying all energy using equipment, product flows and consumption of heating and cooling in the individual processes as well as waste heat streams exchanged with the surroundings.

An example of such a production flow diagram is shown in figure 5 below.

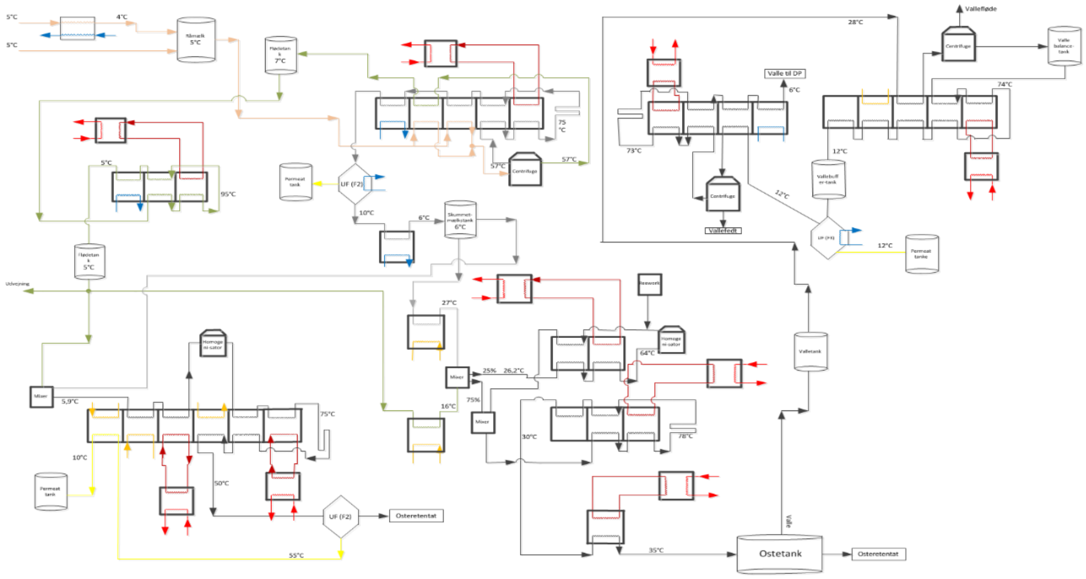


Figure 5. Example of process flows and heat exchangers in a dairy

Such flow diagrams might be established from P & ID-diagrams from suppliers or from inspection of process screens in control rooms, but should be reduced to only illustrate equipment, product flows and heating and cooling supplied to each step of the production. Similar to the level 1 energy mapping, focus should also be on achieving the required data without measuring on all the equipment. Instead of measurements, mass and energy balances can often provide an easier way to achieve many of the values needed. A simple example of such energy balance can be shown for a single generic process as shown in figure 6 below.

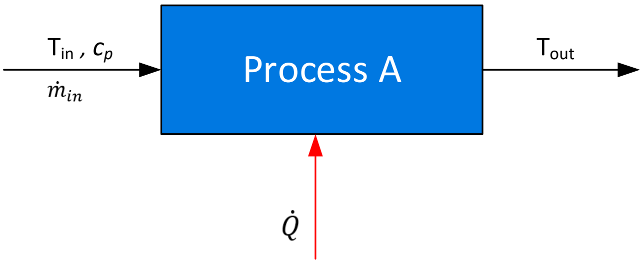


Figure 6. Example of a process requiring heating for setting up an energy balance

The energy balance then becomes:

$$(T_{out} - T_{in})[K] \times c_p \left[\frac{kJ}{kg * K}\right] \times \dot{m}_{in} \left[\frac{ton}{year}\right] \times 1000 \left[\frac{kg}{ton}\right] \times \frac{1}{3600}\left[\frac{h}{s}\right] = \dot{Q}\left[\frac{kWh}{year}\right]$$

Based on the known inputs the above equation can be solved for either temperatures (T), mass ($\dot{m}$) or energy ($\dot{Q}$). It is often a good idea to carry out "line-walks" for utility systems to identify which temperatures that are needed at individual heating demands. Figure 7 below shows an example where at steam boiler supplies steam for several heating consumers below 100 °C.

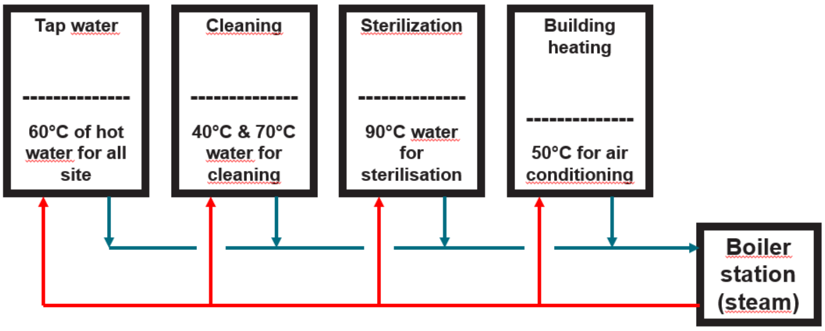


Figure 7. Example of steam supply to low-temperature heating demands.

A similar illustration can be made for cooling systems, where it might be discovered that low-temperature, expensive cooling is used for cooling of high-temperature processes (by example glycol can be seen used for cooling of hydraulic oil).

The result of the level-2 mapping for all heating demands, cooling demands and waste heat streams without existing heat recovery equipment should be a data table like the table 1.

Process	Inlet temperature (°C)	Outlet temperature (°C)	Capacity flow (kW/K)[2]	Hot/cold/waste heat
Pasteurizer				Hot to be cooled
Product cooling				Hot to be cooled
Tank cooling				Hot to be cooled
…				Hot to be cooled
…				Hot to be cooled
Feed water				Cold to be heated
Combustion air				Cold to be heated
Process water				Cold to be heated
…				Cold to be heated
…				Cold to be heated
.				
Flue gas				Waste heat
Cooling tower				Waste heat
…				Waste heat
…				Waste heat

Table 1. Example of data collection for heating and cooling demands and waste heat

---

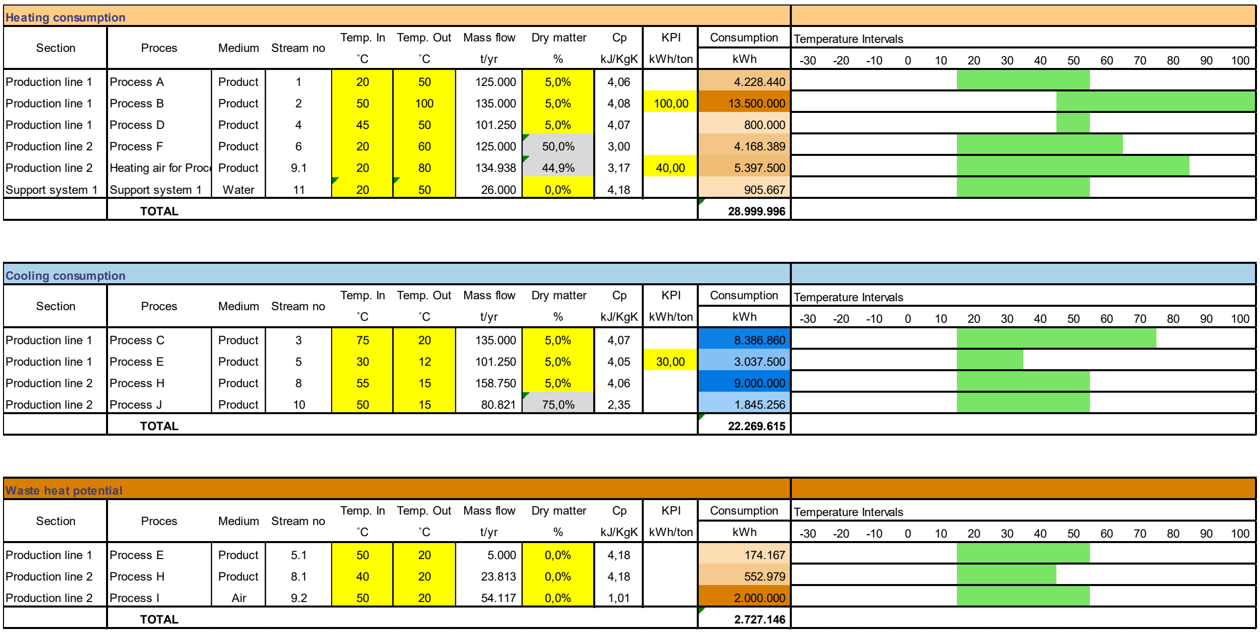
[2] *In this guideline the capacity unit "kW" is used – it could also be "kJ/s"*

In tabel 1, the capacity flow is defined as mass flow of fluid multiplied by thermal capacity of the fluid. The capacity flow expresses how much energy is required /released to change the temperature of the flow by 1 degree. When such data collection has been carried out, a basis for assessment of the full heat recovery potentials in a facility has been established. As the data collection has been carried out assuming that none of the current heat recovery solutions – if any – are applied, the further work aims at identifying the theoretical best possible solutions also implying that existing solutions can be modified or improved.

1.2.3 Temperature intervals

To handle the complex solution-space, where many heat exchanger-solutions can be proposed, a step-wise understanding of the heat recovery potentials should be applied.

A first step can be to present the data from table 1 above in a table also showing temperature intervals of the individual process streams (cold and hot) and waste heat sources as illustrated by the process streams that must be heated in figure 8 below.



Heating consumption

Section	Proces	Medium	Stream no	Temp. In °C	Temp. Out °C	Mass flow t/yr	Dry matter %	Cp kJ/KgK	KPI kWh/ton	Consumption kWh	Temperature Intervals													
											-30	-20	-10	0	10	20	30	40	50	60	70	80	90	100
Production line 1	Process A	Product	1	20	50	125.000	5,0%	4,06		4.228.440						🟩	🟩	🟩	🟩					
Production line 1	Process B	Product	2	50	100	135.000	5,0%	4,08	100,00	13.500.000									🟩	🟩	🟩	🟩	🟩	🟩
Production line 1	Process D	Product	4	45	50	101.250	5,0%	4,07		800.000									🟩					
Production line 2	Process F	Product	6	20	60	125.000	50,0%	3,00		4.168.389						🟩	🟩	🟩	🟩	🟩				
Production line 2	Heating air for Proc	Product	9.1	20	80	134.938	44,9%	3,17	40,00	5.397.500						🟩	🟩	🟩	🟩	🟩	🟩	🟩		
Support system 1	Support system 1	Water	11	20	50	26.000	0,0%	4,18		905.667						🟩	🟩	🟩	🟩					
	TOTAL									28.999.996														

Cooling consumption

Section	Proces	Medium	Stream no	Temp. In °C	Temp. Out °C	Mass flow t/yr	Dry matter %	Cp kJ/KgK	KPI kWh/ton	Consumption kWh	Temperature Intervals													
											-30	-20	-10	0	10	20	30	40	50	60	70	80	90	100
Production line 1	Process C	Product	3	75	20	135.000	5,0%	4,07		8.386.860						🟩	🟩	🟩	🟩	🟩	🟩			
Production line 1	Process E	Product	5	30	12	101.250	5,0%	4,05	30,00	3.037.500						🟩	🟩							
Production line 2	Process H	Product	8	55	15	158.750	5,0%	4,06		9.000.000						🟩	🟩	🟩	🟩					
Production line 2	Process J	Product	10	50	15	80.821	75,0%	2,35		1.845.256						🟩	🟩	🟩	🟩					
	TOTAL									22.269.615														

Waste heat potential

Section	Proces	Medium	Stream no	Temp. In °C	Temp. Out °C	Mass flow t/yr	Dry matter %	Cp kJ/KgK	KPI kWh/ton	Consumption kWh	Temperature Intervals													
											-30	-20	-10	0	10	20	30	40	50	60	70	80	90	100
Production line 1	Process E	Product	5.1	50	20	5.000	0,0%	4,18		174.167						🟩	🟩	🟩	🟩					
Production line 2	Process H	Product	8.1	40	20	23.813	0,0%	4,18		552.979						🟩	🟩	🟩						
Production line 2	Process I	Air	9.2	50	20	54.117	0,0%	1,01		2.000.000						🟩	🟩	🟩	🟩					
	TOTAL									2.727.146														

Figure 8. Example of mapping of thermal loads in a facility including temperature intervals.

From such an illustration (the green bars at the right end of the figure), it is possible to get a first impression of which heat recovery combinations that are possible according to the level of temperatures.

1.2.4 Temperature- and load curves

To deal with the complexity of heat recovery potentials, a first assessment of the potentials should be to establish consolidated for all heating and cooling loads in the facility for each temperature interval as illustrated in figure 9.

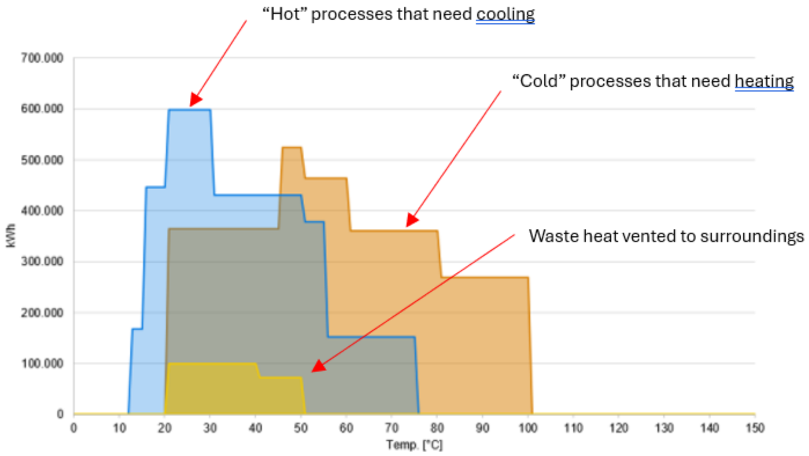


Figure 9. Example of temperatures and thermal loads in an industrial company.

This diagram summarizes all heating loads, cooling loads and waste heat sources in the facility (as mapped in table 1 above) at the individual temperature levels. The diagram can be made by calculating the sum of all hot / cold loads respectively (kWh) in temperature steps of 10-15°C, 15-20°C, 20-25°C etc. as illustrated in the temperature intervals in figure 7 above. The diagram can be constructed applying the Excel-template supporting the mapping-guide described in Appendix 1.

The diagram in figure 9 gives a good picture of the thermal profile of the company, where it for the case presented can be seen that:

- The heat demands in the facility ("sinks" or "cold" processes needing heating) all occur at relatively low temperatures below 100°C.

  When identifying the right source temperatures in a facility this fact is often a surprise when seeing all heating demands are currently covered by steam supply.

- For the facility in the case, quite a significant amount of process cooling of "hot" processes ("sources") occur at temperatures above 30°C indicating potentials for recovering waste heat for process heating.

- Also, the waste heat vented to the surroundings (the yellow area in figure 3) appears to be relevant to look into in further analysis as the waste heat is warm enough to heat certain "cold" processes.

Tools and methodologies for such assessments are well described in the literature[3].

1.2.5 Theoretical heat recovery potential

A simple way to illustrate the heat recovery potential in a facility is to look into the overlaps of "hot" and "cold" streams in figure 9.

In temperature-intervals where "hot" processes to be cooled are warmer than "cold" processes to be heated heat recovery potentials exist.

In figure 10 below, the red area represents an area where cooling (blue area) happens at temperatures higher that the temperatures needed for heating (orange area) and where heat can be transferred in heat exchangers.

---

[3] *The basic methodology for heat recovery analysis is called Pinch Point Analysis, see https://en.wikipedia.org/wiki/Pinch_analysis*

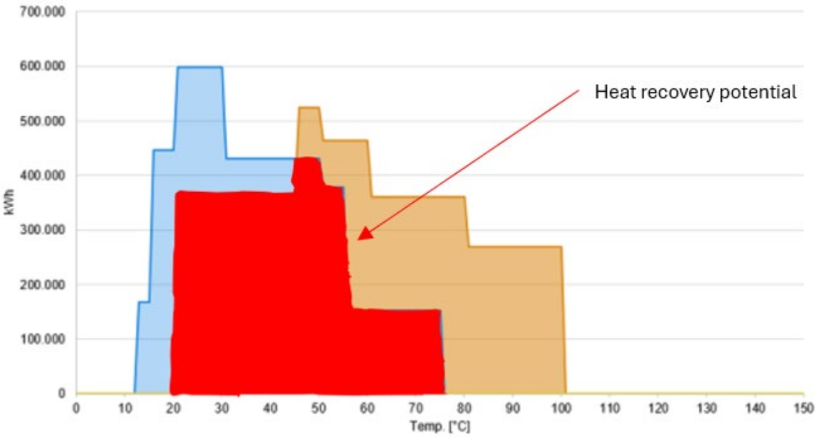


Figure 10. Example of heat recovery potential (red area) in an industrial company

As such, the red area in figure 10 represents the heat recovery potential for the facility in question.

It is (like illustrated above) not unusual that a theoretical heat recovery potential of 30-50% (or even more) is identified, i.e. 30-50% (or more) of the current consumption of fuels for heating can be saved applying heat exchanger networks (HENs). It is important to stress that reduced demand from cooling, that also is a result of such heat recovery, usually is a significant element in the business case for heat recovery.

A thorough and accurate calculation of the heat recovery potential with the data collected in table 1 above is possible applying Pinch Point Technology[4]. The principle of Pinch-Point Technology and cascade-assessments of heat recovery potentials builds on the same principles as described above, but is more detailed and too comprehensive to be explained in this guideline.

1.2.6 Understanding theoretical heat recovery potentials

It is important to understand, that the result for heat recovery potentials illustrated above and/or calculated by such methodologies is a theoretical value that might be complicated to reach in real life.

As such, reaching the full heat recovery potential might necessitate installation of a larger number of heat exhangers, integration of processes over long distances and eventually also installation of hot and cold storage tanks for level out differences in operating hours in different workshops.

A target for the full heat recovery potential is however a valuable basis in the further complex assessment of practical solutions and makes is possible to compare proposed solutions with overall target-values for heat recovery.

1.3 From heat recovery potentials to practical solutions

Overall, the targets for heat recovery potentials as identified above are an important basis for any further work when identifying practical solutions for heat recovery. In principle this work can be approached differently depending on the character of the facility in question:

- A simple approach to identification of heat recovery solutions
- An advanced approach to identification of heat recovery solutions

---

[4] *Reference to tool for Pinch target calculations:* https://natural-resources.canada.ca/maps-tools-and-publications/tools/modelling-tools/integration/24559.

The simple approach is first of all recommended for industries that have simple (few) heating and cooling demands. But also for industries that has been expanding over a long period of time and therefor are very conservative in integrating heating and cooling processes in new ways.

The advanced approach will be used in the case of complex systems with many hot, cold and lose process streams to consider. The advanced approach is also recommended in the case of greenfield projects, where the energy systems for a new facility are to be designed from scratch. The advanced approach might necessitate involvement of experts in Pinch Technology in the project execution.

In chapter 2 below, several examples of international heat recovery projects are presented, but below, a few introduction comments on methodologies for selection of heat exchanger-solutions will be discussed:

1.3.1 A simple approach to identification of heat recovery solutions

In some sectors, the complexity of heating and cooling demands is relatively low – by example in:

- Plastic industry
- Electronics
- Cement industry
- Wood processing
- Iron & steel industry

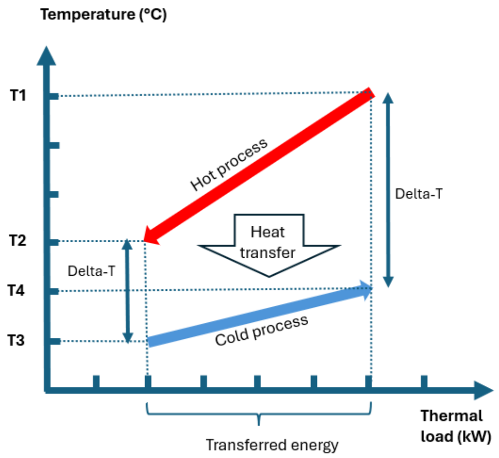
In such sectors – and often also more complex sectors - a simple approach to identification of heat recovery solutions can comprise a sequence of more simple assessments:

- Are existing heat recovery solutions performing well?
- Are existing heat recovery solutions blocking for better solutions?
- Can local heat recovery be applied at individual processes?
- Can other waste heat sources be applied? - possibly using heat pumps?

Each of these simple assessments can be explained further:

- *Poorly performing heat recovery solutions*

  When collecting data for existing heat exchangers it is often observed that these are operated with high delta-Ts, i.e. the temperature differences at each end of the heat exchangers exceeds typical design values (see figure 1 above/below).



The lowest of the delta-Ts measured og calculated at each of the heat exchanger represents how efficient the heat exchanger is operated and should for most types of heat exchangers be below 10°C[5].

High delta-Ts can be caused by wrongly designed heat exchangers, mal-functioning heat recovery systems or by lack of maintenance, by example if heat exchangers are dirty/fouled.

A first and simple step to improve the heat recovery systems in a facility will therefore be to review if existing heat exchangers are performing well or can be improved – either with new heat exchangers or with cleaning of existing heat exchangers. The gain from such improvements can be significant.

- *Existing heat exchangers blocking for better solutions*

  High delta-Ts in a heat exchanger can also indicate that high temperature waste heat (or cooling) is applied for low-temperature heating purposes (or high-temperature cooling purposes).

  Such solutions can block for other and more optimal heat recovery solutions as described in section 1.1 above (i.e. using high-temperature waste heat for medium-temperature heat demands etc.).

  If high delta-Ts are observed at a heat exchanger, it should be investigated if the heat transferred in the heat exchanger can be applied better in another context.

- *Local heat recovery to be applied at individual processes*

  Often individual processes can apply “local” heat exchange, where the outlet stream of the process can be used for preheating the feed stream to the process.

  By example a drier most often will have a warm outlet stream (warm air) that can be used for pre-heating of the inlet air to the dryer (cold air). Another example is a pasteurization process where a cold product needs to be heated to a certain temperature and then cooled again. In this case, a large share of the cooling demand can be covered by the heating demand and vice versa thus saving energy for cooling and heating at the same time. Similarly, a boiler can preheat combustion air lead to the boiler with warm exhaust gas from the boiler.

  Such local heat recovery can be very efficient. The solutions might also be cost-efficient due to short distances between the warm outlet and the cold feed. Finally, outlet and inlets are operated at the same time, and therefore any energy storage can be avoided.

  Often “local” heat exchange at several processes in combination can realize the full, theoretical heat recovery potential without needing any further complicated exercises for construction of advanced heat exchanger networks (HENs).

- *Other waste heat sources? – application of heat pumps?*

  When the potentials described above have been investigated and eventually utilized, certain waste heat sources might remain un-utilized, which then can be assessed as a last step.

  Such remaining potentials are usually found at low temperatures, which necessitates utilization of heat pumps to upgrade the temperature to higher temperatures.

---

[5] *In section 2.1 below, best practices for delta-Ts are presented to typical media and types of heat exchangers*

It is the experience that the simple approach described above might be enough to identify many of the most promising and cost-efficient heat recovery potentials in a facility. Most often, the solutions will also be in line with the identified theoretical heat recovery potentials.

It is always recommended to check if the identified solutions represent a saving potential similar to the identified theoretical heat recovery potential. If not, then the principles of cascade-heat exchange have been violated and the search for optimal solutions must be carried out again.

1.3.2 An advanced approach to heat recovery solutions

A comprehensive and advanced approach to heat recovery solutions (as requested by Pinch Point Technology) is mostly relevant in industrial sectors with multiple and complex heating and cooling patterns, by example in:

- Food and beverage industry
- Chemical industries and pharmaceuticals
- Refineries and petro-chemical industry
- Paper & pulp industry

Reaching the full heat recovery potential in such sectors might necessitate installation of a large number of heat exchangers as well as complex piping arrangements to combine “hot” and “cold” processes the best possible way across the entire facility.

It is outside the scope of this guideline to present a design methodology for each of these sectors, but a few recommendations can be given:

- For the food and beverage industry, the simplified approach presented in section 1.3.1 is almost always enough even though the complex heating and cooling pattern can be complicated to deal with.

  Due to the relatively low temperatures in this sector, a majority of the real-life potential will be found in application of heat pumps to utilize low-temperature waste heat sources.

  The case presented in section 2.7 is typical for solutions in the food and beverage industry – after other solutions have been established as presented in section 1.3.1 above.

- In chemical and pharmaceutical industries, the situation can be very different from one sub-sector to another.

  For large chemical complexes, sub-sector-specific standard solutions will often be a key focus and solutions are to be recommended by preferred suppliers due to risk assessments and guarantees.

  It is however often experienced that existing heat exchangers in these sectors are operated with relatively high delta-Ts, which indicates certain potentials for improvements. In cases where plate heat exchangers are used, it is relatively easy to add more plates to an existing heat exchanger in order to reduce delta-Ts.

- In refineries and petro-chemical industries, applied heat recovery solutions are very sector-specific and a traditional Pinch-Point-analysis will be complicated to perform.

  However new types of heat exchangers have been developed the past few years (fully welded plate heat exchangers) enabling new more efficient solutions to be installed.

Also in the paper and pulp industry, sector specific solutions are usually applied thus leaving relatively few opportunities open for new heat recovery networks.

1.4 Technical barriers towards heat recovery solutions

While heat recovery solutions and heat pumps appear attractive to look into from an energy efficiency and CO2-point-of-view, project developers should be aware of several practical aspects of applying these solutions, first of all:

- Most heat demands in a facility might today be covered by steam heating no matter to which temperatures a process is to be heated to – by example 160ºC of steam (8 bars) are often used to heat water to 80ºC for cleaning purposes.

  The use of steam supply systems is a significant technical barrier for heat recovery systems because most waste heat is too cold to produce steam. Often optimal heat recovery solutions should therefore consider the possibility of installing a hot water supply heat system for heating or preheating the processes in focus – a system that can be operated in parallel to an existing steam supply system. This however comes with an extra cost.

- "Hot" and "cold" processes might not be operated at the same time, i.e. there might not be simultaneity between the processes to integrate in a heat recovery solution.

  This can spoil a good business case because more complex solutions including energy storage will be needed. However, costs for hot and cold water tanks are relatively low and could be feasible to cover by the business case – several solutions have already been designed and build where energy storage (hot or cold) is an integrated part of the heat recovery design.

- The geographical distance between warm and cold processes to integrate might be significant technical barrier necessitating long distance of piping work impairing the business case because of extra investments.

  Further, industries are often skeptical towards integrating different sections and workshops of a facility if these basically are designed to operate independently from each other. By doing this, new constrains are introduced, which can limited the production flexibility.

- Size of the individual source and sinks are also an important parameter, in terms of the feasibility of including the specific source or sinks.

  There is often a lower limit both in terms of energy and capacity, where the integration of a source or sink will not be feasible. This evaluation is both linked to geography as explained above but also to the heat exchanger installation. Several of the costs of the integration of a source or sink is not scalable with the size – by example the installation of meters and control systems - and therefore the "basis" costs can account for a large share of the total costs.

- Utilization of waste heat for process heating will involve installation of heat exchangers with product flows on one side and a heating media flows on the other side.

  For such solutions there can be a risk of cross-contamination if leaks suddenly appear in the heat exchanger. This might be critical in some sectors whereas other sectors don't see such risks. A solution can always be to install an intermediate circuit to transfer the excess heat. This will however reduce the heat recovery potential due to a higher temperature difference between source and sinks.

- In some processes, in-accurate operation of the process will release high amounts of excess heat that can be utilized for heating purposes.

  This is not an optimal path to pursue – a process should always be operated at highest possible efficiency when designing sustainable solutions.

A further barrier might be that available waste heat occurs at relatively low temperatures – in such cases use of heat pumps to bring up the heat to relevant temperatures can be considered.

1.5 The rationale for heat pump solutions

For many industrial sectors, most of the available waste heat is available at relatively low temperatures around 30 - 60°C, by example:

- In cooling towers
- In condensers for refrigeration plants
- In humid exhaust from driers
- In wastewater

Such waste heat sources only have limited potential for direct utilization because most of the heat demand in the facilities occurs at higher temperatures.

In such cases, heat pumps can be applied to lift the temperature of the waste heat to 80 – 90°C, where the potential for use is much higher. Such heat pumps will also be able to cool certain processes, so as the above mentioned sources can be combined with regular process cooling in certain areas.

This principle is illustrated in figure 11 below.

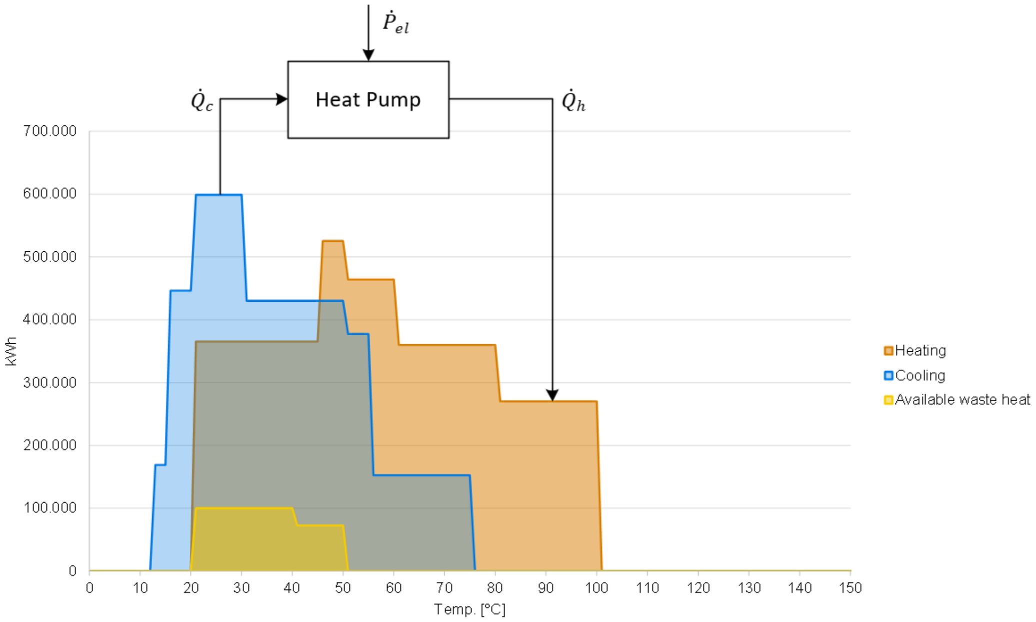


Figure 11. Example of heat recovery potential including a heat pump

For the case illustrated in figure 11, most of the heating demand in the facility can be covered with waste heat when integrating a heat pump producing heat at by example 90 °C.

The solution to do this will be more complicated than traditional heat recovery solutions (a heat exchanger and related piping work) and will include the following installations:

- A cooling water ring collecting waste heat from various sources.

  Such a cooling water ring will to a certain extent be installed in parallel to an existing glycol system, that might be able to cool down certain processes to lower target temperatures.

- A hot water ring delivering the produced heat to various processes.

  Such a hot water ring will to a certain extent be installed in parallel to an existing steam supply that can heat the processes to target temperatures higher than delivered by the heat pump (90 °C).

- A heat pump station integrating the cooling water ring and the hot water ring thus producing heat with a reasonable good COP and there for with an attractive heating price.

- In many cases also storage units on the hot and/or cold side of the heat pump to level out fluctuations in heating and cooling loads across a relatively large number of consumers.

In section 2.7 below, an example of such an installation is described.

Heat pumps might also be applied for individual processes – by example for large dryer systems, where warm air is leaving the drier and cold air needs to be heated before lead to the drier. In such cases, a heat pump can work "across" the dryer with very good COP thus producing heat at an attractive heating price.

In section 2.4 below, such an example is described.

In general, the business case for heat pump solutions can be challenged in cases where electricity is relatively expensive, and fuels are relatively cheap. This can be the cases where biomasses or coal are used as fuel. To make a feasible project, then the COP of the heat pump as a rule of thumb must be higher than the ratio between the electricity price and the price of the fuel that is substituted (i.e. oil or natural gas). But in cases where heating and cooling can be supplied at the same time, the business case is much better because cooling is usually an expensive energy source to produce, see section 2.5 below for such an example.

By experience, the following criteria are therefore important for developing attractive heat pump-installations:

- High operating hours
  - Preferably >4,000 hours per year – and at best at 100% load

- Good COP (>3.5)
  - The temperature difference between "source" and "sink" must not exceed 50 °C

- Simple installations
  - Preferably water/water heat exchange

- Combined heating and cooling
  - See case 2.5 in section 2 below

- At best non-energy benefits can be taken in consideration
  - From capacity increase, quality gains etc.

- Clients are asking for CO2-neutral operations from the suppliers
  - Or even ask the suppliers to demonstrate improved energy efficiency

An important aspect of heat pump installations is that these can be established together with solar PV-plants or wind mills so as heat supply from the heat pumps can be considered as carbon neutral.

This opportunity has a lot of attention in Europe these years, where phasing out the use of fossil use has become a strategic focus for the management on many industrial companies. In Europe, a large proportion of the electricity in the grid is considered carbon neutral because of extensive use of solar PV-plants, wind farms and nuclear power.

1.5.1 Overview of refrigerants for heat pumps

Due to increasing international interest in heat pump-solutions, numerous research and development projects are ongoing aiming at developing heat pumps that can supply a high temperature of the heat – preferably steam consumption.

Even though development work is promising, there still are significant limitations in which solutions that are available.

Table 2 below shows an overview of the present state for different solutions based on sustainable refrigerants.

Technology/ Temperature	**<90°C**	**<120°C**	**<140°C**	**<150°C**
Traditional heat pumps based on ammonia (NH3)	**x**			
New heat pumps with CO2 as refrigerant	**x**	**x**	100 kW test plant in operation	
Heat pumps based on carbonhybrides	**x**	**x**	1,5 MW test plant in operation	2 MW test plant in operation
Heat pumps with new synthetic refrigerants	**x**	2 MW test plant		
Hybrid heat pumps	**x**	Close to market		
Mixed solutions	**x**	**x**		1,5 MW test plant in operation

Table 2. Overview of sustainable heat pump solutions vs. temperatures (non-ozone depletion refrigerants)

A few comments should be added to table 2 above:

- Ammonia heat pumps have recently been installed delivering heat at temperatures up to 95°C, which is to be considered as Best Available Technology (BAT) for this technology.
- CO2-heat pumps are efficient for some purposes, but need large temperature glides for the media both on the cold and warm side of the heat pump to achieve a good efficiency.
- Outside Europe – by example in Japan – solutions are available for generation of heat at higher temperatures (and for steam production), which is technically interesting but environmentally difficult because such solutions use of refrigerants with significant ozone-depletion potential.

Overall the outlook to produce steam at 160°C is not very promising for normal size heat pumps (< 4 MW heating) even though many suppliers state that such solutions are “just around the corner”. The reasons for this experience are several:

- high temperature heat pumps operate at high pressures, which are expensive to build
- high temperature heat pumps are expensive to operate due to low COPs
- high temperature heat pumps require high temperature waste heat, which seldom is available

The last point in this list is important. The COP for a heat pump will be low when waste heat occurs at 30 °C and heat is to be delivered at 120 – 150 °C, which means that the heat price will be high.

For certain large scale purposes (>10 MW), however, new large scale steam producing heat pumps from international suppliers like MAN, Siemens etc. might be relevant to consider, by example in large chemical industries, where heating is needed 8,760 hours per year and COP-values of 2-3 therefore can be accepted.

For such purposes, steam producing heat pumps for base-load operation can considered, but CAPEX for the installations are currently considered to be relatively high also necessitating installation of electric boilers to cover peak demands.

1.6 Waste heat sources in industrial sectors

Character and temperatures of waste/excess heat and cooling of “hot” processes are widely different from one industrial sector to another. Table 3 below shows some examples of the most typical heat sources in different sectors – however even with in a specific sector, sub-sectors can have quite different character.

Sector	Process	Temperature
Food and beverage	Dryers	100-200ºC
	Evaporators	40-70ºC
	Kettles	100ºC
	Cooling towers	30-40ºC
	Process cooling	30-80ºC
	Boilers (exhaust gas)	100-250ºC
	Wastewater	15-40ºC
	Compressed air	60-80ºC
Chemical industry	Dryers	100-200ºC
	Evaporation	40-70ºC
	Distillation	80-100ºC
	Cooling towers	30-40ºC
	Process cooling	30-80ºC
	Boilers (exhaust gas)	100-250ºC
	Wastewater	15-40ºC
	Compressed air	60-80ºC
Cement industry	Rotary Kiln	900ºC
	Cyclones	400ºC
	Raw mill	100ºC
	Cement mill	60ºC
	Exhaust air coolers	350ºC
	Clinker cooler	600ºC
	Compressed air	60-80ºC
Textile industry	Drying	100-200ºC
	Dying	50-80ºC
	Washing	40-80ºC
	Wastewater	15-40ºC
	Compressed air	60-80ºC
	Boilers (exhaust gas)	100-250ºC
Plastics	Hydraulics	40-60ºC
	Compressed air	60-80ºC

	Boilers (exhaust gas)	100-250ºC
Paper and Pulp	Pulper	50-80ºC
	Drying hood	80-150ºC
	Paper machine	80-150ºC
	Dewatering	40-60ºC
	Press	40-60ºC
	Wastewater	15-40ºC
	Compressed air	60-80ºC
	Boilers (exhaust gas)	100-250ºC
Ceramics	Kiln	100-200ºC
	Spray dryer	100-300ºC
	Pre dryer	60-150ºC
	Glassing	60-80ºC
	Wastewater	15-80ºC
	Compressed air	60-80ºC
Steel	Arc furnaces	400-800ºC
	Induction furnaces	600-1200ºC
	Reheating furnaces	200-600ºC
	Casting cooling	80-150ºC
	Cooling water	50-80ºC
	Exhaust air from scrubber	60-80ºC
	Wastewater	15-40ºC
	Compressed air	60-80ºC

Table 3. Example of waste heat sources in various industrial sectors

2 Application of heat recovery and heat pumps solutions

In practice, heat recovery solutions and application of heat pumps comprise a wide variety of solutions and approaches to use of waste heat.

In this section, a number of real-life cases is described to illustrate examples of solutions in this area:

- Optimization of exiting heat exchanger installations
- Process cooling as a heat source
- Utilization of warm waste heat sources
- Heat-pump-integrated processes
- Combined heating and cooling
- MVR-integrated processes
- Centralized heat recovery schemes
- Operation and maintenance of heat exchanger installations

The cases are all collected from European industries and presented with pay-back-periods from these, which might be different in Vietnamese industries. However, the technical opportunities are similar to what has been identified of potentials in Vietnam and the cases can to a wide extend be copied.

2.1 Optimization of existing heat exchanger installations

Many processes and installations have already from the origin been designed with heat recovery solutions according to international standards. By example most pasteurization processes in food processing industries have been built with heat recovery between the cold product stream entering the pasteurization unit and the warm product stream leaving the unit.

It is however the experience that already installed heat recovery solutions can have an efficiency much lower than expected because of several reasons:

- Since the installation of the heat exchanger equipment there has been a significant change of operating parameters like product flows and temperatures so as the equipment is not designed to the current state of operation

- Heat exchangers might be fouled and dirty thus impairing the heat transfer coefficient and the overall performance of the heat exchanger

- For heat recovery solutions where hot water is circulating to transfer heat, efficiency of the installation is often measured to be low due to lack of water in the piping circuits (leaks).

- The existing solutions might have been designed to much lower energy prices than seen today – an optimized solution will today include a much larger and better performing heat exchanger when taking new energy prices into account

- New heat exchanger technology might have been developed enabling new and more efficient heat transfer for the specific purpose

From such reasons, it is always relevant to inspect current heat recovery solutions and assess whether these perform well or not.

This can simply be done by mapping delta-Ts for the processes on each side of a heat exchanger and comparing these to best practices for the specific type of media and heat exchanger. In table 4 below, examples of best practice delta-Ts for various heat exchanger technologies is shown (appendix 2 present a wider overview of heat exchanger technologies).

Technology	**Media**	**Best practice delta-T**
Plate heat exchangers	Water/Water	1-3°C
	Steam/water	3-5°C
Shell & Tube	Water/Water	3-5°C
	Steam/water	5-10°C
Fully welded plate heat exchangers	Water/Water	1-3°C
	Steam/water	3-5°C
Extended surface (fins)	Water/air	1-3°C
Regenerative (rotary/fixed matrix)	Air/air	1-3°C

Table 4. Best practice design temperatures for different heat exchanger technologies

A good activity will always be to review exiting heat exchangers and inspect with which delta-Ts these are operated and from such an investigation decide if significant losses in heat recovery potential is seen due to bad performance of the heat exchanger. Often manual temperature measurements must be carried out to make such an assessment.

<u>Case: Expansion of existing heat exchanger installation in vegetable oil production</u>

In a factory producing food and cosmetic oils the last part of the production line comprises a cooling of oil from 120 °C down to a temperature ≈35°C.

Currently this cooling takes place in two stages using two traditional plate heat exchangers.

- In the first stage, the oil is cooled from 120°C to 50°C in a heat exchanger where the released heat is recovered for heating of hot water from 30°C to 90°C to production purposes.
- In the second stage, the oil is cooled to a target temperature of 35°C with seawater.

Because the first stage heat exchanger is too small, the second stage heat exchanger using seawater must be applied.

The current operation of the system is illustrated in figure 11 below.

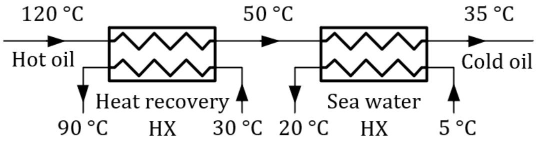


Figure 12. System before heat recovery action.

By adding more plates to the first stage heat exchanger (a simple change) much more heat for heating of water can be recovered thus saving fuels for heating of water in other areas of the facility.

In this case, upgrading of the plate heat exchanger to a delta-T of 5 degrees is possible (compared to a delta-T for the current stage 1 heat exchanger of 20°C) so as the existing seawater heat exchanger only shall be applied as back-up cooler like illustrated in figure 13 below.

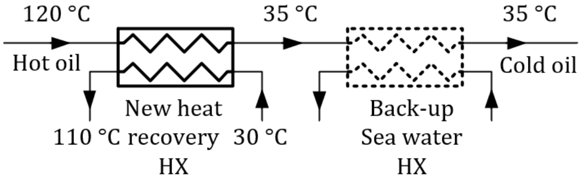


Figure 13: System after heat recovery action.

The key data for this optimized solution is shown in table 5 below.

Natural gas saving [MWh/yr]	Total energy saving [MWh/yr]	Yearly economic saving [k€/yr]	CAPEX [k€]	Payback time [yr]
1400	1400	50	110	2.2

Table 5. Key figures for upgrading of a plate heat exchanger in a vegetable oil facility.

In case the second stage cooling was done with a refrigeration plant (as seen in many other food and beverage industries), the pay-back time for this solution will be very short (< 6 months).

2.2 Process cooling as a heat source

Overall, heating of processes in industrial companies are almost always followed by a cooling process releasing a certain amount of the heat needed for the initial process heating. The remaining part of the supplied heating can end up in waste heat streams vented to the surroundings, by example from driers and kettles for boiling of a product.

As such comprehensive cooling solutions are needed in most industries thus collecting heat that at best can be utilized for heating purposes.

An important part of preparing heat recovery solutions should therefore be to follow cooling water systems (“line walk”) and map which processes that are cooled and at which temperatures the heat can be released – i.e. to fill out the rows “hot to be cooled” in table 4 above.

In this mapping it is important to distinguish between process cooling done with refrigeration plants and process cooling that is done via cooling towers (“natural cooling”).

Process cooling often occurs at high temperatures with immediate opportunities to utilize the heat released during the cooling.

Case: Heat recovery from process cooling

In beer production a solution of malt sugars and hops (the solution is called “wort”) is boiling for approximately one hour with a high heat demand.

A first opportunity for heat recovery is to recover the heat in the vapours from the wort boiling kettle. A second opportunity is to utilize the heat released when cooling down the wort to 10-15 °C just after the boiling process and before going to the fermentation processes.

At an existing brewery raw water at 8 °C is already heated to 80 °C by cooling the hot wort, (figure 13). The heated raw water is used for the next batches of beer production and is stored in hot water tanks to level out differences in timing between the processes. The heating of raw water cools the boiled wort to ≈20 °C and the additional wort cooling heat exchanger cools down to 10-15 °C with a glycol cooling loop.

The existing solution is illustrated in figure 14 below.

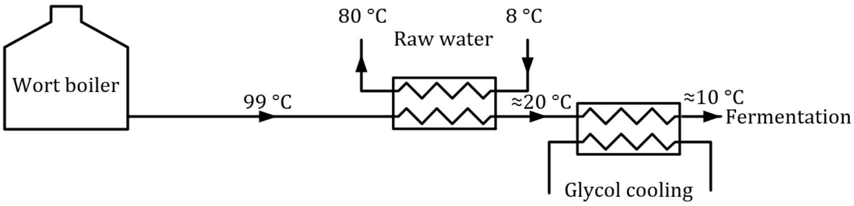


Figure 14: System before heat recovery action.

A new heat recovery system to introduce in this facility is to install a heat exchanger before the raw water heat exchanger. The new heat exchanger heats up a water loop from 62 °C to 90 °C while cooling the boiled wort from 99 °C to 92 °C as illustrated in figure 15 below.

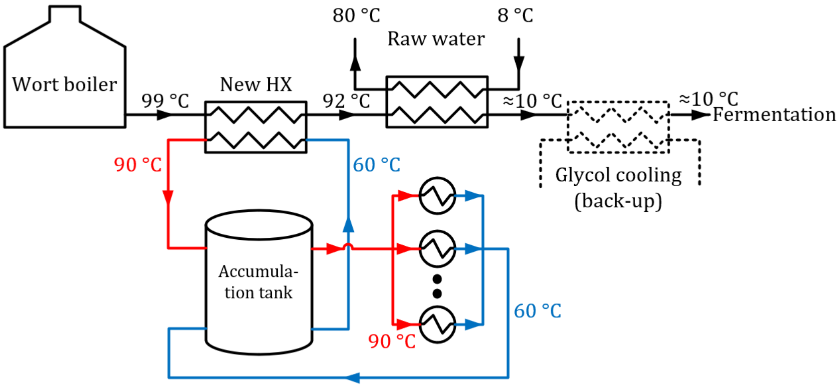


Figure 15: System after heat recovery action.

The heated water loop is also supplied with heat from the boiling process and the heat is distributed around the brewery to heat consumers. The heat recovery solution also eliminates the usage of the glycol cooling loop as the raw water is cooled to the required 10-15 °C by the existing raw water heat exchanger.

As such, the heat recovery action saves both fuel for heating and electricity for cooling systems. The below business case only includes the installation of the new heat exchanger.

Natural gas saving [MWh/yr]	Electricity saving [MWh/yr]	Total energy saving [MWh/yr]	Yearly economic saving [k€/yr]	CAPEX [k€]	Payback time [yr]
2750	750	3500	120	90	0.8

Table 6. Key figures for installation of new heat recovery solution in a brewery.

This case illustrates that heat recovery solutions combining process heating and process cooling can have very low pay-back-periods due to significant savings in fuels and electricity at the same time.

2.3 Utilization of warm waste heat sources

In several sectors, large amounts of warm waste heat are vented to the surroundings and is available for heat recovery solutions, by example:

- In the agricultural sectors, grain driers etc. produce large amounts of warm, humid air
- In certain food industries, driers produce large amounts of warm, humid air
- In cement industry, kilns and klinker coolers ventilates warm air to the ambient
- Etc.

Some of such heat sources are attractive to utilize while others contains dust from the drying process necessitating solutions for cleaning the air before utilization.

Case: Indirect heat recovery on spray drying

At a chemical industry spray drying of the product into powder is done by blowing dry hot air into a cyclone tank while the product is sprayed out at the top of tank.

During the process, water is evaporated from the product as moisture in the air which is sent to the exhaust. At the air inlet to the drying process, the air is cooled to the dew point and below in a dehumidifier to achieve a low relative humidity of the drying air. After de-humidification, the air is re-heated to 120 °C through a heat exchanger with steam as heating medium. The humid exhaust air from the cyclone is 50 °C and goes through a bag filter before being sent to the atmosphere.

The current construction of the system is illustrated in figure 16 below.

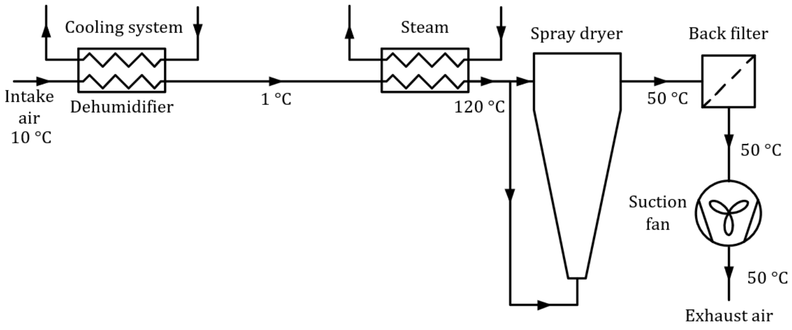


Figure 16: System before introduction of heat recovery.

To reduce the steam consumption, a liquid-coupled heat recovery system is introduced to transfer from the warm, humid outlet air after the bag filter to the re-heating of de-humidified air to the dryer.

As such, two heat exchangers are introduced in the process, where one is on the air intake and the other is on the exhaust air. The two new heat exchangers are connected by a water loop. The exhaust air heats up the water which is pumped to the intake where it does the first part of the re-heating between the dehumidifier and the steam heat exchanger.

The heat recovery system heats the intake air to ≈40 °C, and the steam heat exchanger does the temperature lift to 120 °C. The exhaust air is sent to the atmosphere at ≈10 K above the intake air temperature.

The principle of this solution is shown in figure 17 below.

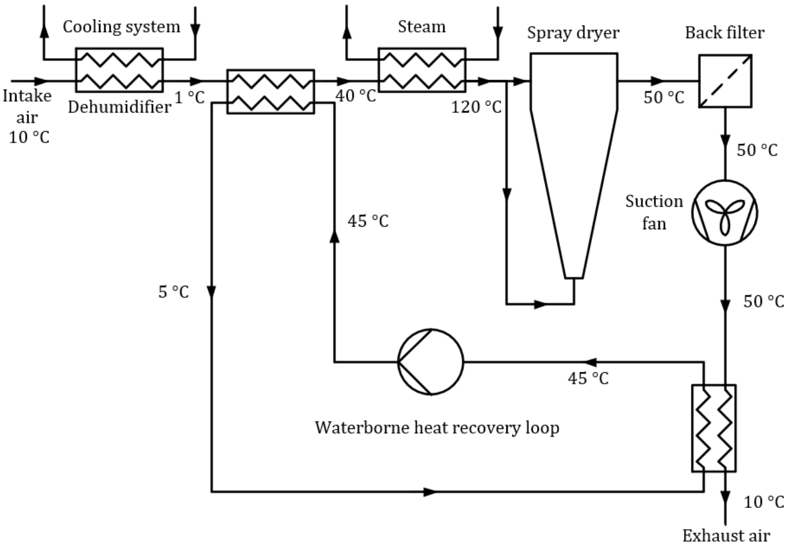


Figure 17: System after heat recovery action.

As the drying process is energy intensive, the energy saving achieved with this solution is significant however with relatively long payback-time due to the relatively large heat exchangers applied in the solution.

Natural gas saving [MWh/yr]	Total energy saving [MWh/yr]	Yearly economic saving [k€/yr]	CAPEX [k€]	Payback time [yr]
2000	2000	80	390	4.9

Table 7. Key figures for installation of new heat recovery solution in a spray dryer.

The challenge for this type of solution is that some industries have to install a relatively expensive bag filter at the outlet not to block the heat exchangers with dust. Such solutions are however already seen at a range og Vietnamese industries.

2.4 Heat pump-integrated processes

In processes like the spray dryer process illustrated above, the heat recovery potential between inlet and outlet can be increased by utilizing the waste heat as a heat source for a heat pump producing heat at a significantly higher temperature.

Typically, traditional heat pumps can deliver heat up to a temperature of 90°C, which enables opportunities for covering a much larger proportion of process heating utilizing waste heat.

As explained in previous sections of this guideline this benefit however comes with an extra electricity cost for operation of the heat pump as well as extra investments in the heat pump that usually is more expensive than simple heat exchanger installations.

Case: Integration of heat pump in drying process

In a maltery, grains need to be dried at the end of the malting process. It is common practice to use a drying kiln with a large area where hot air at ≈75°C is blown through a layer of grains to ensure homogeneous drying. The hot dry air entering the dryer removes water from the grains so as the air becomes more humid at a lower temperature and then led to the atmosphere.

This principle is illustrated in figure 18 below.

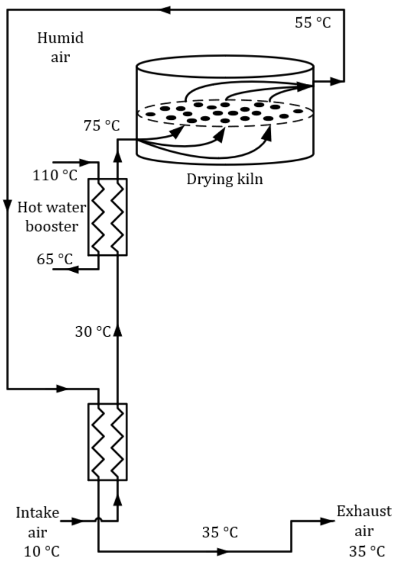


Figure 18: Malt drying system before introducing a heat pump for heat recovery.

A heat recovery solution can be made in two stages:

- Firstly, the exhaust air can be directly coupled to the intake air by heat exchanger.This first stage lifts the intake air to 30 °C.

- The second stage is to integrate a heat pump. The source for the heat pump is the humid exhaust air from after the first stage heat recovery heat exchanger. The heat pump heats the 30 °C intake air to 60 °C and the existing hot water system then lifts the temperature to 75 °C. The heat pump-compressor uses electricity but with a coefficient of performance (COP) of ≈4 meaning that 1 kW of electricity results in 4 kW of heating. The business case includes only the heat pump integration assuming that the stage one heat recovery is already completed.

Below, this 2-stage heat recovery solution is illustrated.

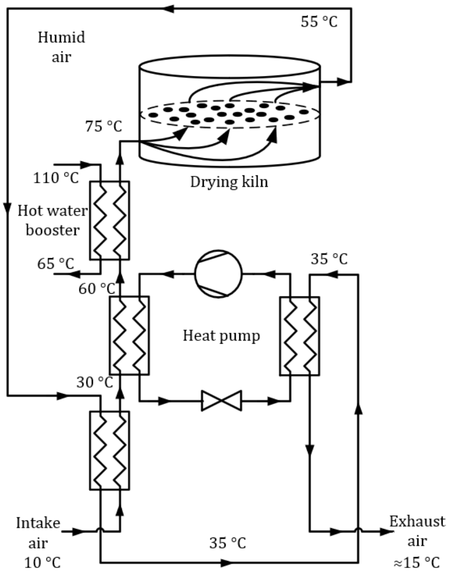


Figure 19: Malt drying system including a heat pump for heat recovery.

Due to the high heat loads in the process, this solution recovers a lot of heat in the process, but it is also a complex and expensive solution with an overall payback time of approximately 5 years.

Natural gas saving [MWh/yr]	Increased electricity [MWh/yr]	Total energy saving [MWh/yr]	Yearly economic saving [k€/yr]	CAPEX [k€]	Payback time [yr]
60000	16000	44000	970	5100	5.3

Table 8. Key figures for installation of a process integrated heat pump in malt drying kiln.

Similar solutions can be introduced to a wide variety of solutions and many industries in Europe look into such opportunities these years to eliminate use of fossil fuels.

2.5 Combined heating and cooling

In some sectors like food industry, chemical industry and pharmaceuticals, comprehensive refrigeration systems are operated to cool processes while also heat is needed at relatively low temperatures (<50°C), by example for preheating of processes and raw materials or for heating of water for cleaning purposes (CIP-systems).

Instead of installing new heat recovery installations, it can be possible to use the existing refrigeration plants to produce heating by increasing the temperature in the condenser to a level where the heat can be utilized, by example a condenser pressure of the magnitude 50°C.

Such operational parameters will impair the efficiency (COP) of the refrigeration plant and thus increase electricity consumption, but the business case is often simple and very good.

Such solutions can also utilize the waste heat in oil coolers and de-super heaters in the refrigeration plant.

<u>Case: Hot water heating in a pharmaceutical company</u>

Pharmaceutical companies are an example of industries where process cooling can require large refrigeration plants at the same time as boilers using fossil fuels are operated for production of hot water.

Figure 20 below shows the key data for a solution where the pressure in the condenser of the refrigeration plant producing chilled water at 6°C is increased to a level (close to 50°C) where water can be heated to 45°C.

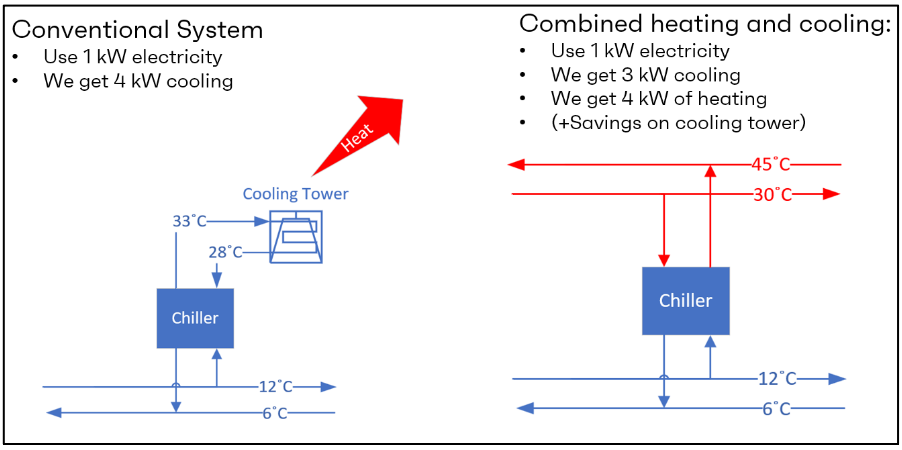


Figure 20. Example of combined heating and cooling in a pharmaceutical company.

In this case the conventional system consumes:

- 1 kW of electricity (to produce 4 kW of cooling)
- 4 kW of fuels for heating

By the combined heating and cooling, the system consumes 1 kW of electricity to produce 3 kW of cooling and 4 kW of heating. As such, the cooling output is reduced 1 kW (i.e. 25%) when producing 4 kW of heating.

2.6 MVR-integrated processes (Mechanical Vapour Recompression)

Certain industrial processes produce vapours when heating and boiling a product, by example:

- Wort boiling in breweries
- Evaporator lines in chemical industries and food ingredients
- Distillation columns in pharmaceutical and chemical industries

The vapours contain large amounts of waste heat as boiling of a substance – water as well as solvents – requires a significant heat load to change phase of the product from liquid to vapour.

In such cases, there is an opportunity to integrated vapour recompression in the process, where the vapours are taken through a compressor, increasing pressure and temperature of the vapour to a level where the vapour is warm enough to heat the boiling process itself. Typically, a temperature lift of just 5-7°C is enough to operate the process.

The principle of MVR is illustrated in figure 21 below.

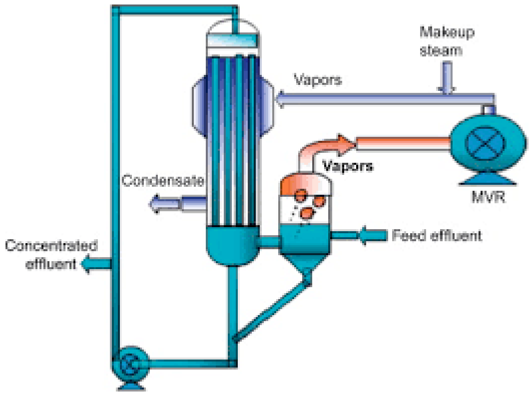


Figure 21. Principle of mechanical vapour recompression (MVR).

Overall MVR-solutions can be considered as a type of a heat pump – however with an extremely high COP due to the low temperature lift over the compressor. Often COP-values of 20-30 can be achieved in MVR-plants.

Case: MVR for evaporation process in food ingredients facility

At a Danish food ingredients facility, an evaporation process is required to concentrate a liquid juice extracted from raw materials. A thin concentration of juice enters vaporizers where water is evaporated to produce a thick and concentrated juice.

The existing vaporizers are operated as traditional thermal evaporator heat with steam from a central system, see the principle illustrated in figure 22 below.

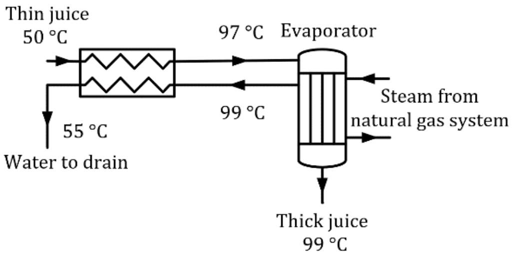


Figure 22: Traditional evaporator system heated with plant steam

A heat recovery solution will in this facility, be to integrate a mechanical vapour recompression (MVR) system on the evaporator.

In this solution, evaporated vapour from the product is firstly separated from the liquid part in a separator. The vapour is then compressed in a turbo compressor to raise the pressure and temperature, then to be fed back to the evaporation process but now as the driven force for evaporation, i.e. as a heating media on the other side of the heat exchanger.

This solution is illustrated in figure 23 below.

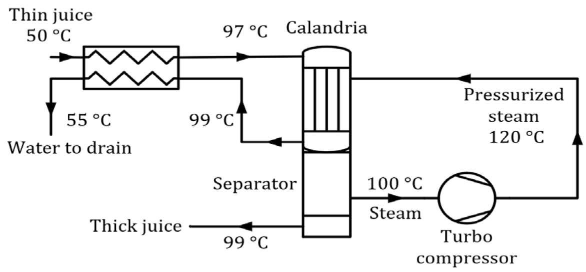


Figure 23. Evaporator system with integration of MVR-solution.

After the recompressed steam has been used to evaporate new incoming product, it is sent to drain or potentially to other heat recovering purposes before drain. The evaporation process requires a completely new setup using a falling film evaporator where the unit is called a calandria. The MVR system acts as a heat pump reducing energy usage significantly.

Due to the complicated nature of the solution, the payback time from a pure energy efficiency point of view is long as seen in table below.

Natural gas saving [MWh/yr]	Increased electricity [MWh/yr]	Total energy saving [MWh/yr]	Yearly economic saving [k€/yr]	CAPEX [k€]	Payback time [yr]
27500	5500	22000	770	6700	8.7

Table 9. Key figures for installation of an MVR-evaporator

Such complex solutions however often are established for other reasons than just reducing energy consumption, by example for increasing capacity of an old plant. In case, a new-build facility is to select between a traditional evaporator and a MVR-plant, the payback-time for the MVR-solution will be much lower than calculated in table 9 above.

2.7 Centralized heat recovery schemes

A significant new development in heat recovery solutions in many European industries is to establish centralized heat recovery systems, where waste heat is collected from several sources and used in heat pumps producing hot water for process heating in several areas of the facility.

Typical waste heat sources collected are:

- Heat from compressed air plants (oil cooling)
- Heat from refrigeration systems (condensers, oil coolers and de-superheater)
- Heat from process cooling
- Eventually waste heat from boilers

Such a solution is relevant where low-temperature heating demands exist. A hot water heating distribution system can be established to fully or partly cover certain heat demands in the facility.

As such the solution is relevant mostly in food industries, in chemical industries and phamaceuticals, while the solution is not relevant in high temperature process industries, such as cement and steel industries.

Case: Centralized heat recovery system in a diary

A dairy has various processes which require a wide range of temperatures and utilities. The utilities include heating, cooling, electricity, and compressed air. Some processes require temperatures above 100 °C, some 80 °C and some 60 °C.

A central heat recovery system can be integrated in the utility structures to reduce the energy usage on site – both electricity for cooling and fossil fuels for heating. The solution is illustrated in figure 24 below.

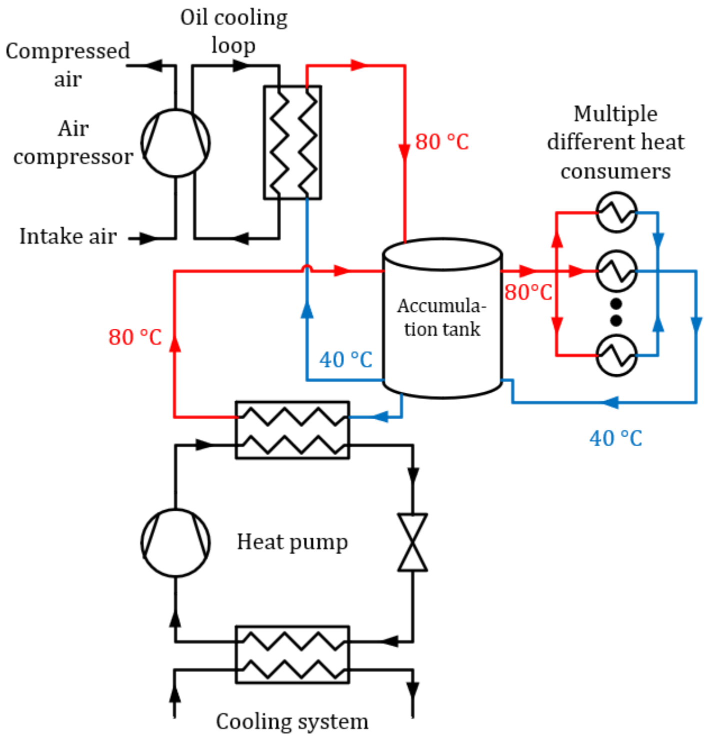


Figure 24: System after heat recovery action.

One element in the solution is to utilize waste heat from a compressed air system. When producing compressed air, 70-80 % of the electricity usage is lost as heat in the air compressors where the compression heat is cooled away to protect the compressors. This heat can be collected at ≈80 °C and be connected to a central water-based heat recovery system.

A heat pump is then integrated into the central heat recovery system. The energy source for the heat pump is the condenser in the refrigeration system. The heat pump lifts the temperature to 80 °C from the 35 °C in the condensor. The heat pump also induces an electricity saving for the refrigeration system.

The recovered heat from the air compressors and heat pump is stored in a large accumulation tank to level out differences in heat loads and availability of waste heat. Different heat consumers requiring heat at or below 80 °C can be supplied with heat from this tank. With free heat from the air compressors and COP of the heat pump, a significant reduction in energy usage is achieved.

In table 10 below, key figures for the solution are summarized.

Natural gas saving [MWh/yr]	Increased electricity [MWh/yr]	Total energy saving [MWh/yr]	Yearly economic saving [k€/yr]	CAPEX [k€]	Payback time [yr]
4600	1350 - 350 = 1000	3600	290	1360	4.7

Table 10. Key figures for centralized heat recovery solution with heat pump in a dairy.

It is seen that the payback-time is relatively long, which partly is explained by the fact that the solution is introduced as a retrofit of an existing plant. In case new heating or cooling capacity is needed, the payback time can be much shorter.

2.8 Operation and maintenance of heat recovery solutions

It is important to be aware that also heat recovery solutions need to be maintained and supervised to maintain a high efficiency of these:

- Heat exchangers are often fouled with dust or remains from a liquid
- Water-based solutions can lose water and be operated with reduced heat transfer
- Insulation of piping, valves and heat exchanger installations shall be frequently inspected and repaired

It is recommended to install meters to supervise the amount of recovered heat from an installation as the efficiency of heat recovery is often impaired over time. Alternatively, temperature sensors shall be installed to monitor if design temperatures for heat exchangers are maintained over longer time spans.

3 Screening, audits and feasibility studies

Due to the potential complex nature of waste heat recovery projects, a careful, well-documented and stepwise development of solutions to establish is recommended.

Usually such work will follow the main phases of:

- An audit or screening phase, where data are collected and immediate energy saving potentials are assessed

- A pre-feasibility phase, where preferred solutions are developed to an extent where investments (CAPEX) and operational costs (OPEX) are well known and can be compared for alternative solution strategies

- A feasibility phase, where a preferred solution is developed to a level where a Final Investment Decisions can be taken by the management of the facility.

Below, main activities in each of these phases are described in more detail with reference to previous sections in the guideline as well as other documents developed under the Danish-Vietnamese cooperation[6].

3.1 Screening and energy audit

The initial assessments of heat recovery potentials can be made as a screening or an energy audit following the pertaining regulation[7] and supplementary guidelines[8]. In any case, the work should aim at mapping the current situation in the company and any potential for saving energy via heat recovery and integration of heat pumps.

3.1.1 Initial data collection for heating and cooling demands etc.

The initial data collection should provide an overview of heating and cooling demands in the facility, which – with reference to section 1.2 above – will comprise:

- Yearly energy consumption of thermal energy:
  - Natural gas and LPG
  - Coal
  - Biomass
  - Etc,
- Yearly consumption of electricity
- Current energy prices

Based on these gross-numbers, a breakdown of the annual thermal and electrical energy should be established for main unit operations and utility systems. This should be done in parallel to establish full and detailed flow sheets for the facility which explain all product flows and process steps where energy is added or removed.

Usually, such a mapping (level 1-mapping) is presented in pie-charts and flow diagrams like illustrated in section 1.2 of this guideline.

---

[6] *Link to guidelines for pre-feasibility studies and feasibility studies.*

[7] *Link to Circular 25*

[8] *Link to energy audit guideline*

3.1.2 Level-2-mapping of heating and cooling demands etc.

When assessing heat recovery potentials the next phase of mapping work – usually called “level-2-mapping” - is critical important comprising the following data collection:

- Mapping of temperatures and capacity flows for all individual heating demands
- Mapping of temperatures and capacity flows for all individual cooling demands
- Mapping of temperatures and capacity flows for all waste heat streams

These data are to be presented in tables like table 1 above in section 1.2.2.

On the basis of these data, temperature/load-diagrams for the entire facility should be established (see figure 6 and 7 above) and an immediate potential for heat recovery should be assessed.

In this phase, also an overview of the current utility systems should be established:

- What is the state and efficiency of current heat supply

- The savings achieved with heat recovery might increase significantly when losses in boilers and heat distribution systems (steam) are taken into account.

- What is the state and efficiency of current cooling supply (refrigeration plants and cooling towers)

- The savings achieved with heat recovery utilizing process cooling as a source might increase significantly when losses in the cooling station and chilled water/glycol heat distribution systems (steam) taken into account.

Such a detailed basis is necessary to establish for a full understanding of heat recovery potentials.

3.1.3 Heat recovery solutions

The further work in the audit/screening phase shall identify specific heat recovery solutions and assess first estimates for the technical and economic feasibility of these.

As such specific projects must be defined:

- Which heating and cooling processes and waste heat streams to integrate
- Should the heat recovery systems be central or decentral or a combination of both.
- Which utility systems to integrate in the solutions
- Which heat exchanger to establish or increase the size of

Immediate technical barriers shall be identified such as lack of simultaneity, distance between “source” and “sink”, risks of cross-contamination in heat exchangers etc.

For the preferred solutions, energy savings, CO2-emission reductions and simple payback periods should be estimated and preferred solutions concluded.

The identified solutions should be compared the overall heat recovery potential identified by the temperature/load-curves.

3.1.4 Reporting from screening/audit

As a minimum the initial screening/audit should present and document the following results:

- A summary of data collected for individual process streams (heating, cooling and waste heat)

- An overview of which losses and efficiencies the various utility systems are operated with, i.e. heating plants and cooling plants

- An assessment of which overall saving potentials that can be achieved with heat recovery and heat pumps

- A survey of recommended solutions to look further into

- If relevant, a first estimate of related “non-energy benefits” should be listed

- A proposal for priority of further work to be undertaken in order to get more precise estimates of investment costs and benefits for the most promising improvement solutions.

The screening/energy audit should be presented at management level to discuss observations and to align proposed solutions with other facility plans (capacity expansions etc.). Based on such a presentation, conclusions on further work should be reached.

3.2 Pre-feasibility study

A pre-feasibility study shall be conducted in order to more accurately describe and compare different heat recovery and heat pump solutions that can be considered.

The aim of this work is to identify, quantify and compare specific solutions in terms of technology, investments (CAPEX), operating costs (OPEX) so as these can be presented for the management of the company for further discussion.

The general guideline for pre-feasibility elaborated in the Danish/Vietnamese cooperation studies should be used in order to present the relevant business cases.

3.2.1 Design basis

At this stage it is important to lock the design basis for the project (s), i.e. on which expectations for present and future operation the business cases shall be calculated.

A design basis will usually comprise:

- A summary of current state of operations and any challenge driving a rehabilitation project
- Expectations for present and future production volume for the relevant area of the facility
- Expectations for present and future energy demand
- Expectations for present and future energy prices
- Expectations for any expected CO2-abatement costs
- Expectations for requests to become carbon neutral among clients and in the supply chain

Other questions might be important for the design basis and overall it is strongly recommended to document data in a written memo or report as basis for any further work.

3.2.2 Solution strategies

Most likely, a range of overall type of solutions should be compared in this phase of the project, first of all because:

- Some heat recovery solutions will address optimization of individual processes and unit operations
- Other will integrate waste heat utilization between different processes and unit operations

Therefor different solutions might compete with each other.

It is further important to notice that suppliers of specific processes and unit operations often have standard solutions for heat recovery to look into, where own development of similar solutions might add risks to the current situation.

The important question is therefore to identify a good balance between heat recovery on individual processes and unit operation and more utility-oriented solution, where waste heat and process cooling is collected and used in existing or new heat distribution systems (hot water distribution).

As such, a first activity in this phase will be to take contact to suppliers of the most heat demanding processes to ask for availability of heat recovery solutions. If such are relevant and if pay-back periods are attractive, such solutions are often attractive, but should be compared to other solutions.

A second step in the pre-feasibility phase will then be to look into solutions where process cooling and waste heat from unit operations (that suppliers can't optimize) is collected centrally and used for process heating at temperatures below 100°C.

For each identified solution, investments (CAPEX) and operating costs and savings (OPEX) should be identified so as simple payback periods can be calculated. This will involve dialogue with suppliers as well as companies capable of doing necessary piping work and electrical work that is often an important part of heat recovery solutions.

3.2.3 Non-energy benefits

Non-energy benefits from waste heat recovery are mostly related to assessment of capacity questions for cooling and heating plants influenced by heat recovery solutions.

This question might however be important to quantify:

- Can capacity be saved on the boiler station so as planned capacity expansions can be avoided when introducing heat recovery?

- Can capacity be saved on refrigeration plants and cooling towers so as planned capacity expansions can be avoided when introducing heat recovery?

On the other hand it shall also be assessed if new heat recovery solutions will necessitate extra maintenance work.

The value of non-energy benefits should be assessed from an economic perspective at this stage of the project development and might be equally important as benefits from improved energy efficiency.

3.2.4 NPV-assessments (Net Present Value)

For relevant solution strategies/alternative business cases, the Net Present Value (NPV) should be assessed in order to compare total investment- and operating costs over a relevant period of time – by example 10 years.

A NPV-assessment requires that each alternative project option is to be assessed by:

- Investments (CAPEX)
- Operating costs (OPEX) for

- Energy
- Maintenance
- Labour
- Other related questions

Typically, the NPV-approach allow for comparing high-CAPEX solutions with low operating costs (OPEX) low-CAPEX-solutions with high OPEX.

At this stage it might also be relevant to initiate dialogue with banks on financing options, as certain loan opportunities for sustainable solutions might have better conditions than traditional loans.

Each relevant solution strategy is to be presented including data CAPEX, OPEX, NPV, ROI and payback-periods.

3.2.5 Management meeting

On the basis of the pre-feasibility study, a meeting with the management of the company should be arranged to present results from the analysis and conclude on a preferred case for further work.

3.3 Feasibility Study

The purpose of the feasibility phase is to present a final preferred solution to the management so as a Final Investment Decision (FID) can be made.

By that, a preliminary solution design from the pre-feasibility phase shall be prepared and accurate expectations for investments (CAPEX) and operating costs (OPEX) should be made. The feasibility study guideline provides general advice to how to do a feasibility study link. Below are some specific recommendations to feasibility study of heat recovery systems.

3.3.1 Scope for project

As a first activity in the feasibility phase, the scope of the project shall be locked.

A project might address individual heat recovery solutions as well as centralized solutions and the feasibility phase should clarify in detail which works that are to be planned, by example:

- Solutions delivered by suppliers
- Building works
- Electrical works
- Piping and plumming work
- Automation systems
- Etc.

It shall be carefully described what the preferred project will comprise and who is expected to carry out work for each of the involved disciplines.

3.3.2 Preferred supplier (s)

To get accurate information on specific solutions, expected investments and operating costs, a dialogue will most often have to be initiated with relevant suppliers.

For some areas – by example electrical and mechanical works - the company most likely already have preferred suppliers.

For large investment projects, external consultants might be needed to prepare the FS and bidding documents. .

3.3.3 Preliminary solution design

Drawings and 3D-animations should be developed to present a visual solution design for the preferred solution (s).

The main scenario and relevant sub-scenarios should be described in terms of investment costs and operating costs so as the management of the company can make decision on a preferred path forward.

Still – at this stage – suppliers are to be involved in the project development to an extent where the preferred solutions can be presented – where a tendering process at a later stage will enable the company to select the supplier with the most advantageous solution.

3.3.4 Financing

For major rehabilitation or replacement projects, the company will most often need to seek external financing of the investments.

For the dialogue with financing institutions, a summarizing feasibility study-report should be prepared.

3.3.5 Final investment decision (FID)

On the basis of the feasibility study-report and financing proposals from relevant financing institutions, the management of the company should be able to make a final decision on the preferred project.

Appendix 1. User guide for carrying out energy mappings

Introduction

A careful mapping and understanding of the energy usage in an industrial company is a crucial baseline in project development.

However, in numerous international projects it has been observed that energy auditors face severe challenges in such important work, partly because the work is not very well structured and well defined in terms of outputs, and partly because energy auditors are reluctant to build conclusions on other than detailed and precisely measured data.

With this background, this guide aims to establish a well-defined mapping methodology, that delivers clear outputs phase by phase and supports and instructs energy auditors on specific activities to be carried out.

The guide consists of an energy mapping template in Excel format which is accompanied by the present user guide which describes how to set-up such a mapping in practice and how to utilize the results for developing projects. The data and process flow within the energy mapping template are only for illustrative purposes and do not represent actual data from an actual production site.

Figure 1 shows a flow chart of the overall energy mapping process which can be used to keep track of the steps in the energy mapping process. It also highlights the iterative process of setting up the energy balance, where the mapping degree is used as an indicator for when to move on to analyse the results. This simplified approach can save auditors a lot of time on carrying out many very time-consuming measuring programs on all equipment and instead focuses on first getting a full overview of the actual energy demands based on available information and assumptions. This enables the auditor to prioritize the more time consuming analyses and measuring programs on the processes and equipment that is initially shown to have the greatest saving potentials. Having set up energy- and mass balances for a process will often also be a necessary step for identifying which parameters to measure.

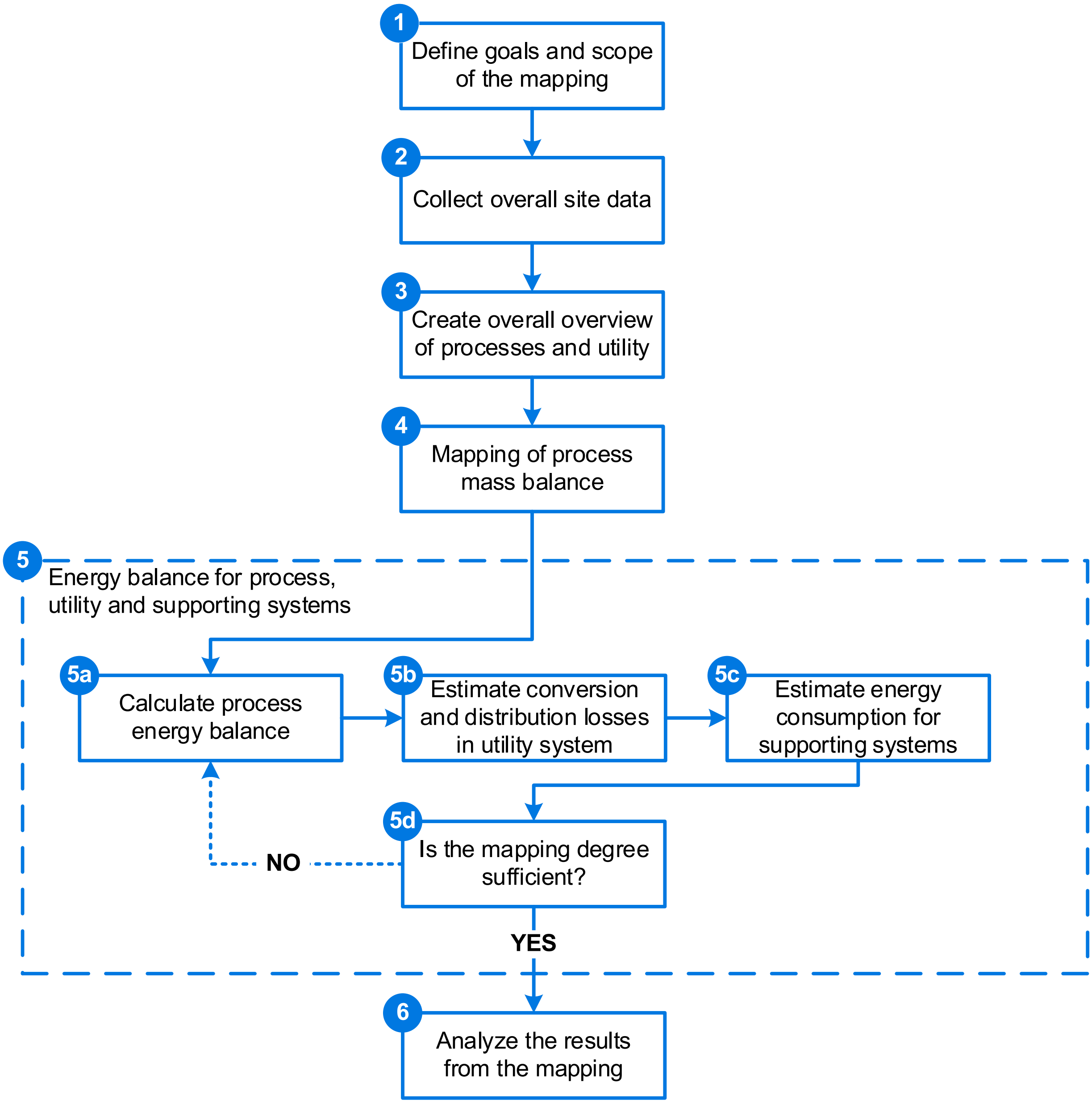


Figure 1: Flow chart of the energy mapping process

Defining a scope and goal

This first step of the energy mapping is to clearly define a scope and purpose for the energy mapping. Depending on the size of the company and timeline for the energy mapping and the overall strategy of the company which is being mapped, the scope and goals of the mapping could vary. The following questions should therefore be considered before starting the energy mapping:

- Is the goal to map the entire facility or should the mapping focus on certain areas?
  - Geographic areas?
  - Certain production areas of higher interest?
- What level of detail can be achieved with the given timeline for the energy mapping?
- What is the main driver for conducting the energy mapping?
  - Is it only to achieve a detailed overview of the energy consumption?
  - Is it economical? Should the mapping be prepared to handle economic evaluations?

- Is it environmental? Should the model be prepared to handle CO_2 savings as well?

Overall site data

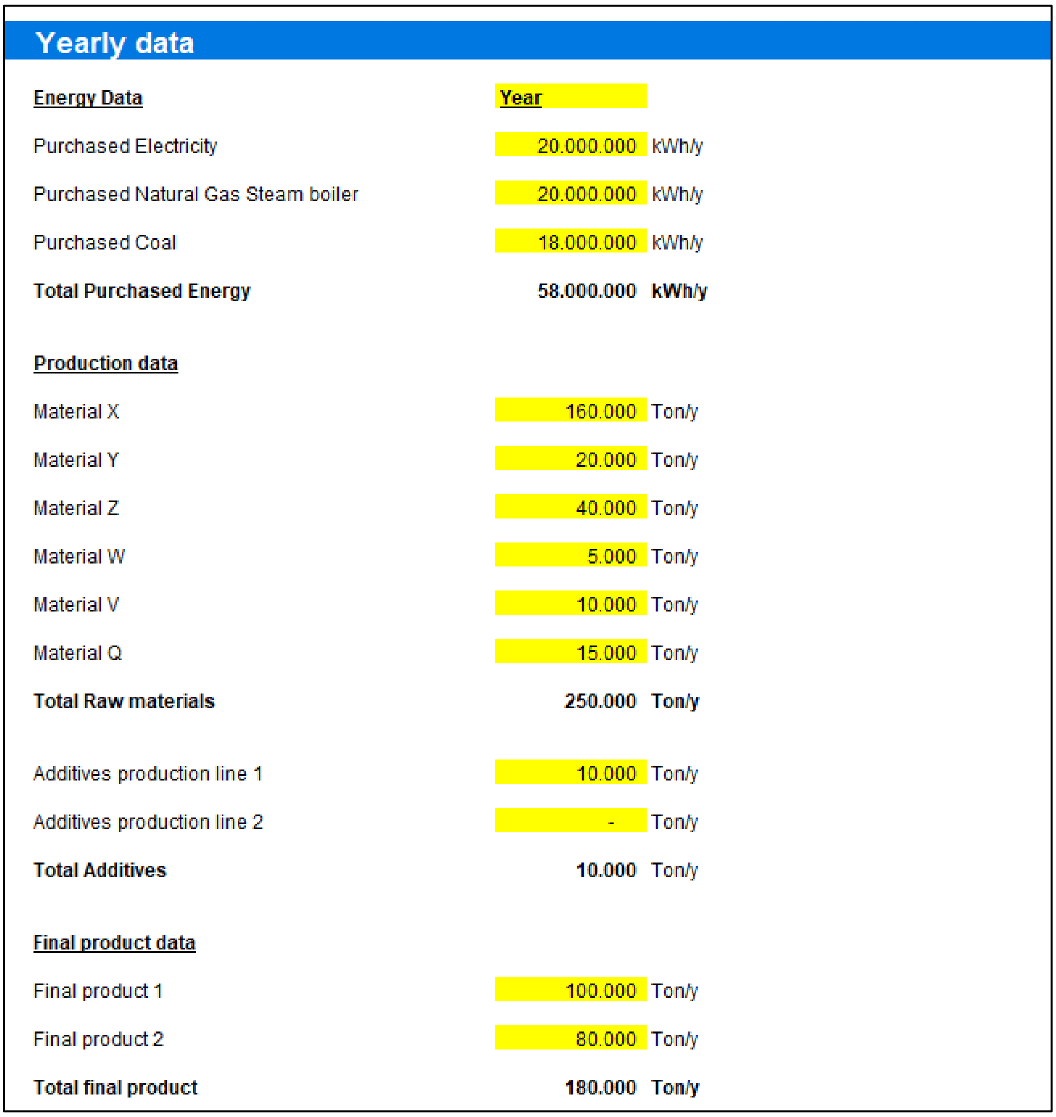
When the scope is defined, the next step of the energy mapping is to get an overview of the overall site data. This data should be easily available at most sites. The overall site data covers all purchased primary energy consumption and the amount of production output. In addition to the outputs the main inputs (i.e. raw materials) to the production process should also be obtained at this step. In the Energy mapping template, an example of such overall data collection is shown in the sheet “Yearly data”.

This sheet will function as an input sheet for the mass balance and utility mapping sheets later on. Therefore, all unit conversions should be carried out in this sheet to avoid unnecessary calculations in the later sheets. It is important to secure consistency of the units within all data types. For time, energy and mass, the recommended units are:

1. Time: Year
2. Mass: Tons
3. Energy: kWh

Being consistent about all units will ease further work and comparisons.

The overall site data should be collected as soon as possible and many times even before an actual site visit, in order to give a better understanding of the size of the production company and their overall energy demands.



Yearly data

Energy Data	**Year**	
Purchased Electricity	20.000.000	kWh/y
Purchased Natural Gas Steam boiler	20.000.000	kWh/y
Purchased Coal	18.000.000	kWh/y
Total Purchased Energy	**58.000.000**	**kWh/y**
Production data		
Material X	160.000	Ton/y
Material Y	20.000	Ton/y
Material Z	40.000	Ton/y
Material W	5.000	Ton/y
Material V	10.000	Ton/y
Material Q	15.000	Ton/y
Total Raw materials	**250.000**	**Ton/y**
Additives production line 1	10.000	Ton/y
Additives production line 2	-	Ton/y
Total Additives	**10.000**	Ton/y
Final product data		
Final product 1	100.000	Ton/y
Final product 2	80.000	Ton/y
Total final product	**180.000**	**Ton/y**

Figure 2: Overview of collection of overall site data. See sheet "Yearly data" in the Excel template.

Creating an overview of process, utilities and supporting systems

Once the overall site data has been gathered and goals and scope have been defined, an overall overview of the production processes, utilities and supporting systems should be created. These are essentially the first drafts of what will become the mass flow balance and utility mapping in the Excel template.

The overviews should be made on the basis of screenshots, flow diagrams, previous audits, production trends, site walks, etc. This first overview can also be carried out on paper or a drawing program such as Visio to then later be carried over to the Excel spreadsheets. An example of a simple Visio sketch of the example from the Excel template is shown in Figure 3.

For the production processes the goal is to create a basic overview of the entire production flow at the site. At this step, the focus is to include all processes in the right order in relation to each other, but not necessarily to get numbers on inputs and outputs of each step. Every process should be labelled and each process stream should.be numbered to keep a good overview of the system. The production flows are mapped in the sheet “Mass flow balance” in the Excel template.

In addition to creating an overview of the production processes, an overview of the utility structures at the site should also be prepared. Once again focus at this stage is more to qualitatively achieve the full overview rather than quantifying losses and efficiencies. This should be done for all utility systems at the site (i.e. heating, cooling, compressed air, etc.). The utility structures are mapped in the sheet “Utility mapping” in the Excel template.

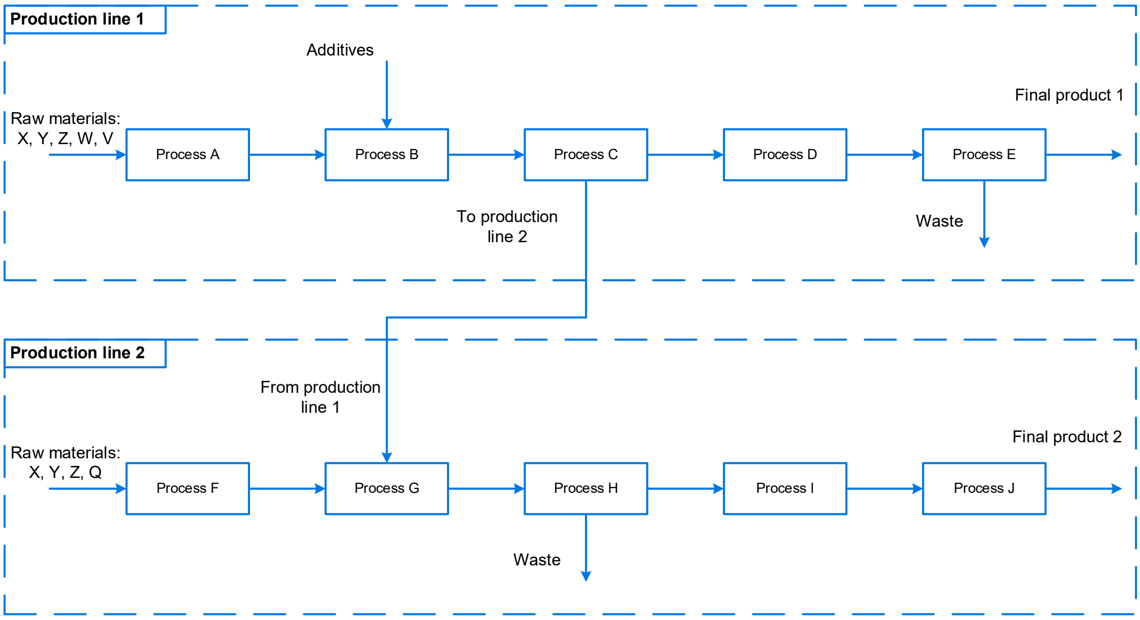


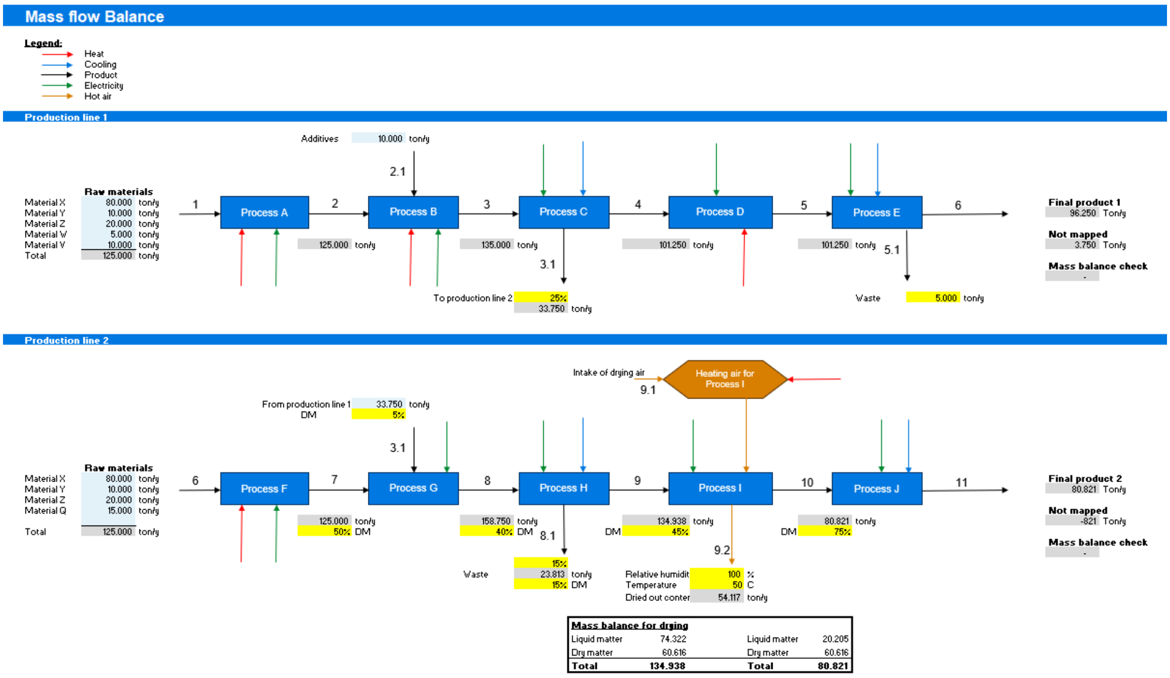
Figure 3: Simple Process flow overview of the template example.

Process mass balance

The next step is to set up the process mass balance based on the previously created process flow diagram. This is shown in Figure 4 below and is done in the “Mass flow balance” sheet in the mapping template. Each process step is indicated by a box. The example shows a site with two different production lines that are creating two different products from a list of raw materials. Each production line consists of 5 processes with varying inputs of additives and energy. It is also seen that a byproduct from production line 1 is used directly in production line 2. To carry out the mass balance the following steps should be followed:

1. The yearly data for raw materials are imported from the “Yearly data” sheet.
2. For each process it is evaluated whether there is any addition or extraction of material.
3. If any product or additive is added or removed during a process, data should either be collected from the company if possible or it should be estimated.
    a. Estimation can often be done by consulting the operating personnel at the site.
    b. For some processes calculating the mass balance could require more information about the product. In the energy mapping template such an example is given for production line 2, where the mass balance is set up from knowing the Dry Matter percentage between process steps.
    c. This process can require a more detailed understanding of the process than the auditor has and it can therefore be an advantage to involve operational or production personnel with extensive knowledge on the process in this step.
4. All streams with additions or removal of product are numbered.
    a. It is important remember to include waste streams since these might become interesting for later analysis

5. It is important to keep progressing with the energy mapping and not get stuck in trying to achieve a value in a very detailed way that takes too long at this stage. If the uncertainty of a value is deemed very high this should be noted by the energy auditor as a potential focus point for later analysis.
6. When all processes have been mapped, the calculated amount of final product can be compared to the actual data for final production. This can be used to indicate if there are significant errors in the mass balance.
    a. In addition to this, a check should also be done for each production line on all incoming materials and outgoing products, making sure it equals out (In the Excel template this is carried out in cells T25 and T52 for the two production lines respectively).



Raw materials		
Material X	80.000	ton/y
Material Y	10.000	ton/y
Material Z	20.000	ton/y
Material W	5.000	ton/y
Material V	10.000	ton/y
Total	125.000	ton/y

Raw materials		
Material X	80.000	ton/y
Material Y	10.000	ton/y
Material Z	20.000	ton/y
Material Q	15.000	ton/y
Total	125.000	ton/y

Mass balance for drying			
Liquid matter	74.322	Liquid matter	20.205
Dry matter	60.616	Dry matter	60.616
Total	**134.938**	**Total**	**80.821**

Figure 4: Overview of the process mass flow balance. See sheet "Mass flow balance" in Excel template.

Energy balance for process, utility and supporting systems

In addition to the mass flow balance, energy balances for process, utility and supporting systems should be set up. The goal is to set up tables for each utility type where all the energy consumers are listed. This is shown in Figure 5 and can be seen in sheet “Process mapping” in the Excel template. Starting with the process energy balances the recommended approach is described below:

1. The first step is to evaluate the energy inputs for each process on a qualitative level, considering both the thermal and electrical energy consumption. This is most easily done by drawing ingoing energy flows on the previously created mass balance. This can also be seen in Figure 4.
2. After this, the specific energy consumption in each process step should be calculated. Each process is listed in the respective energy consumption tables and some basic information on “Section”, “Media” and “Stream No.” is noted for easy reference later.
3. For thermal energy mapping additional information on the process stream might be required. In any case temperature information is needed and, in some cases, pressure and heat capacity or enthalpy could also be needed. The mapping itself can be carried out with three different approaches (examples of all three approaches are given in the Excel template):
    - **Flow**: With the flow approach, the energy demand is calculated with the following equation. This approach is based on information of the mass flow and temperature difference over a specific unit.

$$(T_{out} - T_{in})[K] \times c_p \left[\frac{kJ}{kg * K}\right] \times \dot{m}_{in} \left[\frac{ton}{year}\right] \times 1000 \left[\frac{kg}{ton}\right] \times \frac{1}{3600}\left[\frac{h}{s}\right] = \dot{Q}\left[\frac{kWh}{year}\right]$$

   - **KPI**: With the KPI approach, the energy demand is calculated based on a KPI for the specific unit, if such information exists.

     $$KPI\left[\frac{kWh}{ton}\right] \times \dot{m}\left[\frac{ton}{year}\right] = \dot{Q}\left[\frac{kWh}{year}\right]$$

   - **Measurement**: With measurement approach, the energy demand from a component will be measured over a period of time and the measured value will be extrapolated to a yearly consumption. It can also be that the energy consumption for a given process is logged by the production company.

4. It is important to keep in mind that the potential energy content of the process waste streams should also be mapped during the thermal energy mapping.
5. For the electrical energy mapping, the electricity consumption of the process equipment is calculated. This calculation can also be based on three different approaches (examples of all three are once again shown in the Excel template):
   - **Power**: with the power approach then the electricity demand is calculated by the knowledges of the power capacity, the operating hours and a load estimate.

     $$\gamma[-]\ \times t\ [h]\ \times p[kW] = \dot{P}_{unit}\left[\frac{kWh}{year}\right]$$

     t = annual operational time in hours [h]
     γ = Load factor
     p = effect in kW [kW]

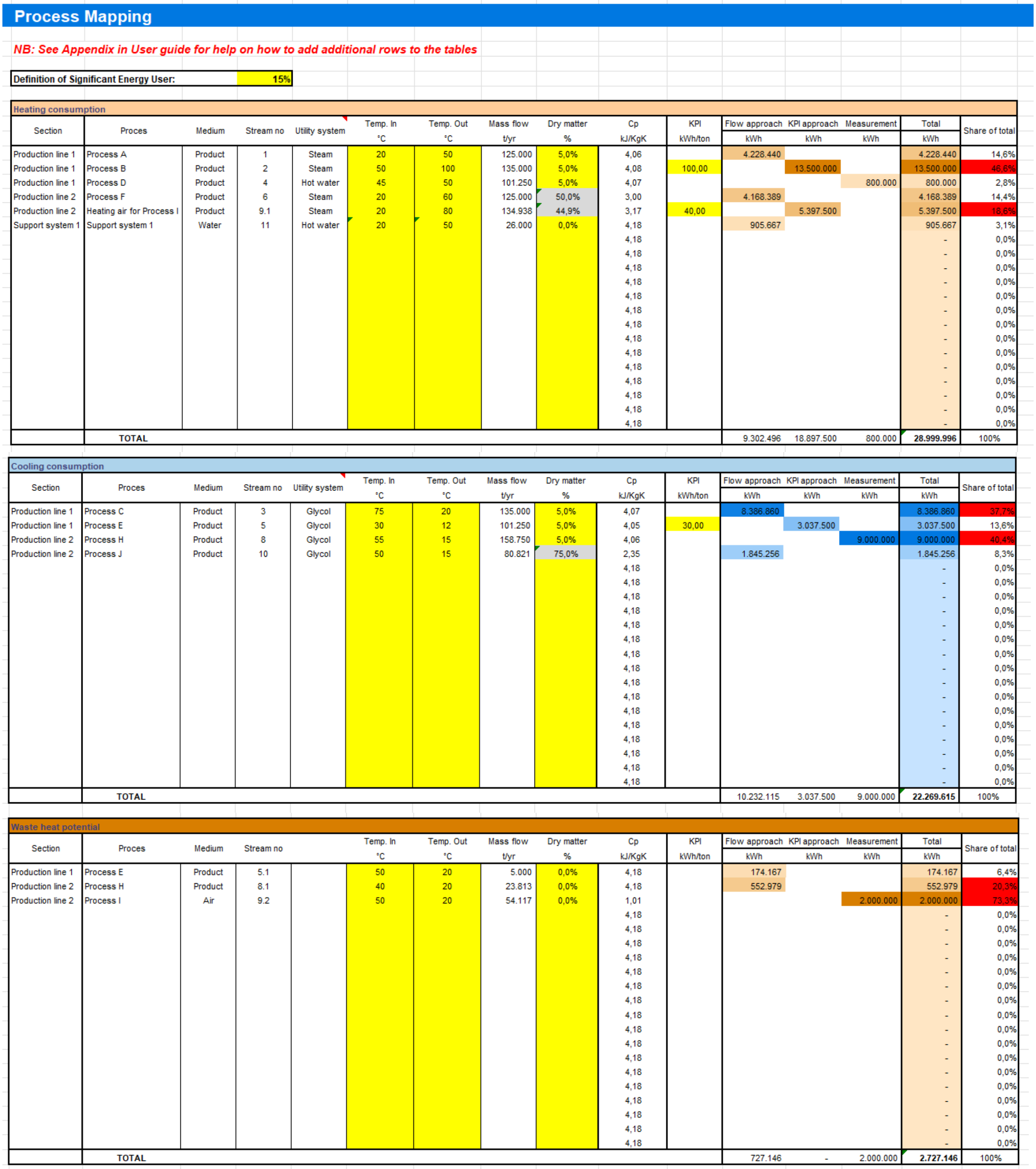
   - **KPI**: This approach is the same as for the thermal part.

     $$[KPI]\left[\frac{kWh}{ton}\right] \times \dot{m}\left[\frac{ton}{year}\right] = \dot{P}_{unit}\left[\frac{kWh}{year}\right]$$

   - **Measured**: This approach is the same as for the thermal part.

     $$\dot{P}_{unit}\left[\frac{kWh}{year}\right] = measured$$

6. The template is set up with conditional formatting to indicate the largest consumers in each energy type. Cell E6 can furthermore be utilized to define a threshold for Significant Energy Users. This can vary depending on the size of the facility and the number of process streams.
7. In column CO to MK a temperature analysis is set up for analyzing results in the later stage.
8. Once again it is important to keep progressing with the energy mapping and not get stuck in trying to achieve a value in a very detailed way that takes too long at this stage. If the uncertainty of a value is deemed very high this should be noted by the energy auditor as a potential focus point for later analysis
9. The tables in the Excel template are set up to be able to handle up to 100 processes within each category. Most of these are hidden to keep a better overview. For a guide on how to unhide a number of rows Appendix 7.1 should be reviewed.



Process Mapping

NB: See Appendix in User guide for help on how to add additional rows to the tables

Definition of Significant Energy User: 15%

Heating consumption

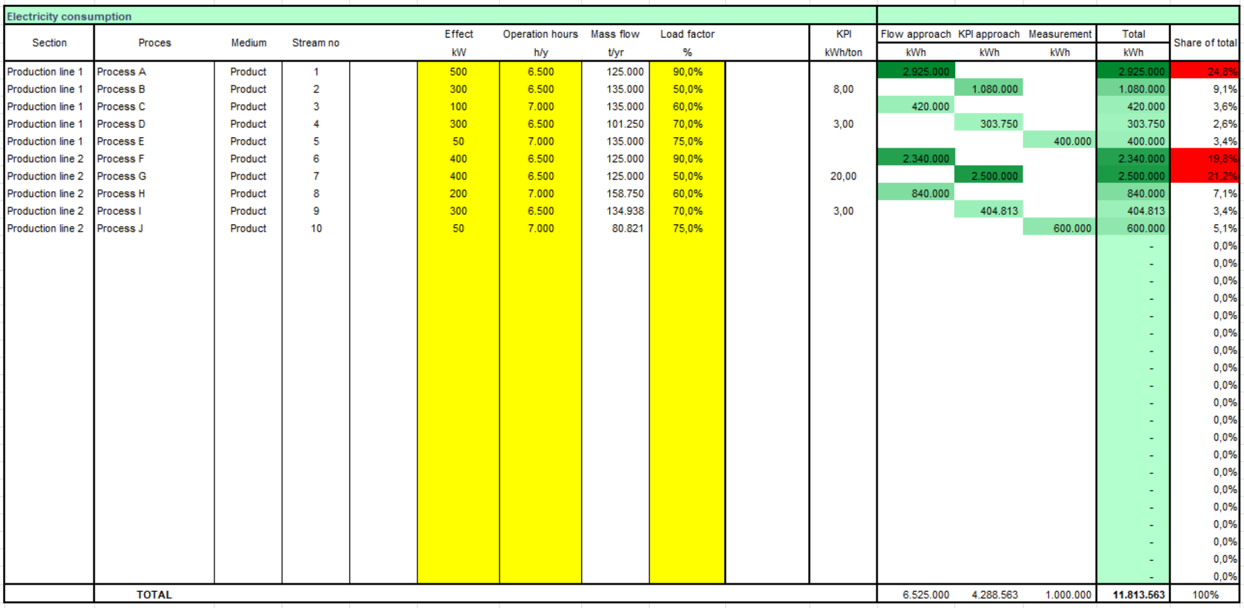
Section	Proces	Medium	Stream no	Utility system	Temp. In °C	Temp. Out °C	Mass flow t/yr	Dry matter %	Cp kJ/KgK	KPI kWh/ton	Flow approach kWh	KPI approach kWh	Measurement kWh	Total kWh	Share of total
Production line 1	Process A	Product	1	Steam	20	50	125.000	5,0%	4,06		4.228.440			4.228.440	14,6%
Production line 1	Process B	Product	2	Steam	50	100	135.000	5,0%	4,08	100,00		13.500.000		13.500.000	46,6%
Production line 1	Process D	Product	4	Hot water	45	50	101.250	5,0%	4,07				800.000	800.000	2,8%
Production line 2	Process F	Product	6	Steam	20	60	125.000	50,0%	3,00		4.168.389			4.168.389	14,4%
Production line 2	Heating air for Process I	Product	9.1	Steam	20	80	134.938	44,9%	3,17	40,00		5.397.500		5.397.500	18,6%
Support system 1	Support system 1	Water	11	Hot water	20	50	26.000	0,0%	4,18		905.667			905.667	3,1%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
	TOTAL										9.302.496	18.897.500	800.000	**28.999.996**	100%

Cooling consumption

Section	Proces	Medium	Stream no	Utility system	Temp. In °C	Temp. Out °C	Mass flow t/yr	Dry matter %	Cp kJ/KgK	KPI kWh/ton	Flow approach kWh	KPI approach kWh	Measurement kWh	Total kWh	Share of total
Production line 1	Process C	Product	3	Glycol	75	20	135.000	5,0%	4,07		8.386.860			8.386.860	37,7%
Production line 1	Process E	Product	5	Glycol	30	12	101.250	5,0%	4,05	30,00		3.037.500		3.037.500	13,6%
Production line 2	Process H	Product	8	Glycol	55	15	158.750	5,0%	4,06				9.000.000	9.000.000	40,4%
Production line 2	Process J	Product	10	Glycol	50	15	80.821	75,0%	2,35		1.845.256			1.845.256	8,3%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
	TOTAL										10.232.115	3.037.500	9.000.000	**22.269.615**	100%

Waste heat potential

Section	Proces	Medium	Stream no		Temp. In °C	Temp. Out °C	Mass flow t/yr	Dry matter %	Cp kJ/KgK	KPI kWh/ton	Flow approach kWh	KPI approach kWh	Measurement kWh	Total kWh	Share of total
Production line 1	Process E	Product	5.1		50	20	5.000	0,0%	4,18		174.167			174.167	6,4%
Production line 2	Process H	Product	8.1		40	20	23.813	0,0%	4,18		552.979			552.979	20,3%
Production line 2	Process I	Air	9.2		50	20	54.117	0,0%	1,01				2.000.000	2.000.000	73,3%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
									4,18					-	0,0%
	TOTAL										727.146	-	2.000.000	**2.727.146**	100%



Electricity consumption

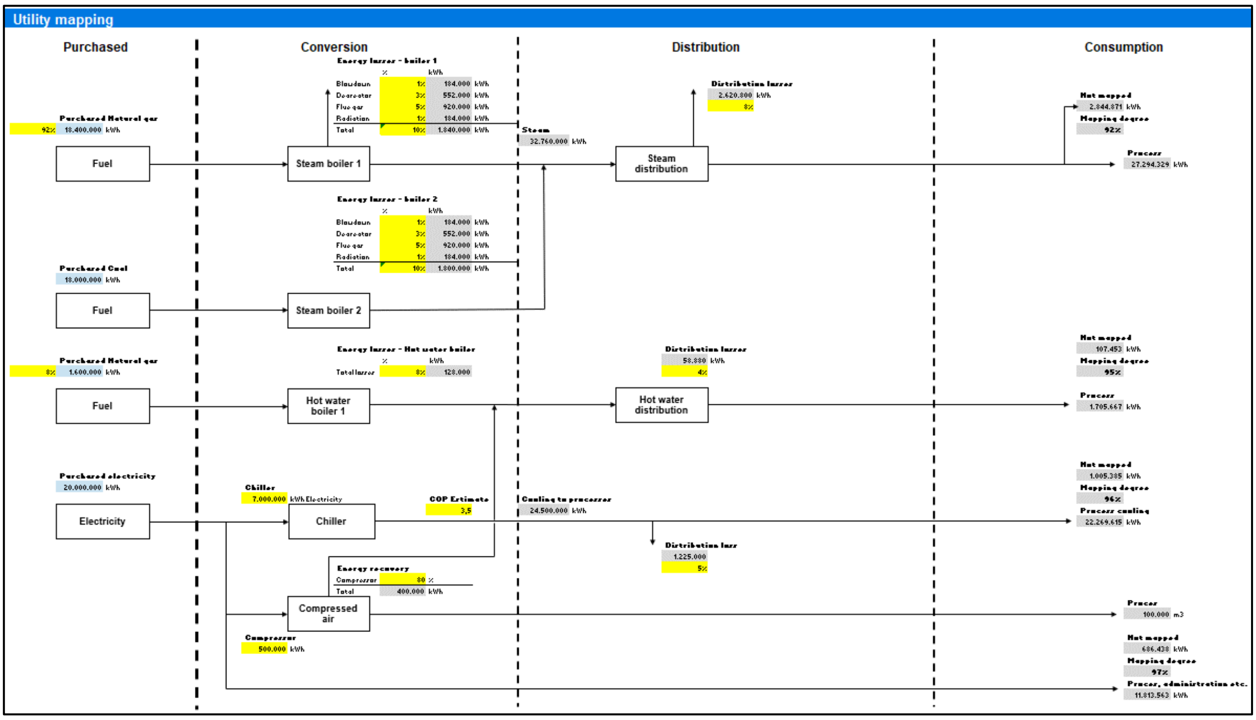
Section	Proces	Medium	Stream no	Effect kW	Operation hours h/y	Mass flow t/yr	Load factor %	KPI kWh/ton	Flow approach kWh	KPI approach kWh	Measurement kWh	Total kWh	Share of total
Production line 1	Process A	Product	1	500	6.500	125.000	90,0%		2.925.000			2.925.000	24,8%
Production line 1	Process B	Product	2	300	6.500	135.000	50,0%	8,00		1.080.000		1.080.000	9,1%
Production line 1	Process C	Product	3	100	7.000	135.000	60,0%		420.000			420.000	3,6%
Production line 1	Process D	Product	4	300	6.500	101.250	70,0%	3,00		303.750		303.750	2,6%
Production line 1	Process E	Product	5	50	7.000	135.000	75,0%				400.000	400.000	3,4%
Production line 2	Process F	Product	6	400	6.500	125.000	90,0%		2.340.000			2.340.000	19,8%
Production line 2	Process G	Product	7	400	6.500	125.000	50,0%	20,00		2.500.000		2.500.000	21,2%
Production line 2	Process H	Product	8	200	7.000	158.750	60,0%		840.000			840.000	7,1%
Production line 2	Process I	Product	9	300	6.500	134.938	70,0%	3,00		404.813		404.813	3,4%
Production line 2	Process J	Product	10	50	7.000	80.821	75,0%				600.000	600.000	5,1%
												-	0,0%
												-	0,0%
												-	0,0%
												-	0,0%
												-	0,0%
												-	0,0%
												-	0,0%
												-	0,0%
												-	0,0%
												-	0,0%
												-	0,0%
												-	0,0%
												-	0,0%
												-	0,0%
												-	0,0%
												-	0,0%
												-	0,0%
												-	0,0%
												-	0,0%
												-	0,0%
	TOTAL								6.525.000	4.288.563	1.000.000	**11.813.563**	100%

Figure 5: Overview of the process energy mapping. See sheet "Process mapping" in Excel template

When the process level energy balances are set-up, the utility level energy balance can be set-up. The utility mapping covers all the utility systems that support the process energy demand. The utility systems can be boilers, coolers, chillers, air compressors, wastewater etc. The scope is to cover the purchased energy, conversion of energy, distribution of energy and finally the process energy. An example is shown in Figure 6 and can furthermore be seen in the Excel template. This system consists of two steam boilers using coal and natural gas to supply the main heating consumption, while a small hot water boiler and waste heat from air compressors is used in a 60°C system to supply hot water for supporting systems and one low temperature heating process. Cooling is supplied by one central chiller. The Excel template is prepared to handle up to three heating and cooling systems respectively. If more systems are present, the later results will have to be expanded by the user. The utility mapping can be carried out by the following steps:

1. All purchased energy is imported into the “Purchased” column
2. All major utility equipment is added to the “Conversion” column e.g. in the example the system consists of two steam boilers, chillers and air compressors.
3. For each type of equipment, the efficiency is estimated, and energy losses are calculated.
    - In the example losses are estimated for the boilers and air compressors
    - For chillers a Coefficient-of-Performance (COP) and known electricity consumption is used to estimate the amount of cooling that is produced. The COP value is not always known by the site in which case it might have to be estimated based on an assessment of the present equipment.
4. Next, the distribution losses are estimated in the “Distribution” column based on an overall assessment of the distribution system (level of maintenance, insulation, steam traps etc.)
5. Then the utility is connected to the end-users in the “Consumption” column.
6. Finally, the overall mapping degree can be calculated. As shown in Figure 1 in the beginning, the mapping degree is now used to evaluate whether the mapping is done to a sufficient degree or whether an extra iteration is required to.
    - If the mapping degree is deemed too low the energy balances are reevaluated.
    - If the mapping degree is deemed sufficient the auditor can move on to setting up and analyzing the results.
    - The sufficient level can vary a lot depending on the size of the facility and level of detail. Based on international experience a mapping degree of at least 90% is most often

considered sufficient. However, no matter the degree it is very important to critically reflect on the reasons why it is not exact and what the potential consequences can be.



Energy losses - boiler 1

	%	kWh	
Blowdown	1%	184.000	kWh
Deareator	3%	552.000	kWh
Flue gas	5%	920.000	kWh
Radiation	1%	184.000	kWh
Total	10%	1.840.000	kWh

Energy losses - boiler 2

	%	kWh	
Blowdown	1%	184.000	kWh
Deareator	3%	552.000	kWh
Flue gas	5%	920.000	kWh
Radiation	1%	184.000	kWh
Total	10%	1.800.000	kWh

Energy losses - Hot water boiler

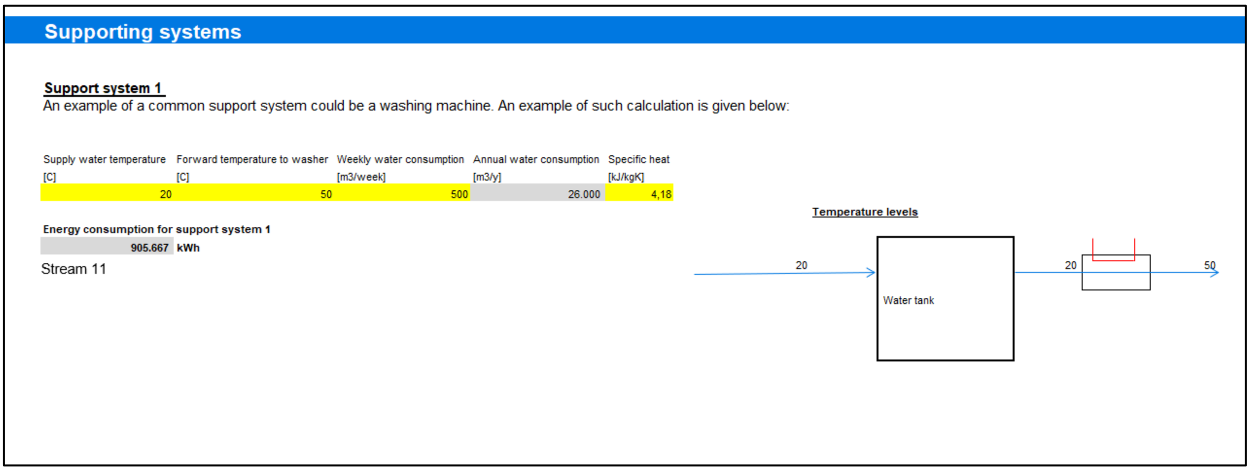
	%	kWh
Total losses	8%	128.000

Energy recovery

Compressor	80	%
Total	400.000	kWh

Figure 6: Overview of the utility mapping. See Excel template sheet "Utility mapping".

In addition to process and utility level energy balances, many production facilities also have several supporting systems. These systems are also required to be mapped, to get the full overview of energy consumption at a site. Examples could be, Cleaning-In-Place, washers (containers, boxes, bottles etc.), ventilation, packaging units etc. Since these will not be visible in the process flow, a separate sheet in the Excel template is kept for handling of these systems "Supporting systems". In the Excel template one example is given which is shown in Figure 7 below. In this example steam is used for heating up water for a washing machine at the site. This energy consumption is also carried over to the process mapping overview tables.



Supporting systems

Support system 1

An example of a common support system could be a washing machine. An example of such calculation is given below:

Supply water temperature [C]	Forward temperature to washer [C]	Weekly water consumption [m3/week]	Annual water consumption [m3/y]	Specific heat [kJ/kgK]
20	50	500	26.000	4,18

Energy consumption for support system 1

905.667 **kWh**

Stream 11

Figure 7: Overview of the supporting systems. See the sheet "Supporting systems" in the Excel template

Analyzing and understanding the results

When a sufficient mapping degree is achieved, the next step is to set up the results in an easily understandable way. To use the energy mapping properly it is important to consider how to present the results and how to use the results efficiently develop energy saving projects. It is emphasized that the development of projects should start by understanding the energy consumption of the processes before moving on to the utility systems. A full understanding of the actual energy service or purpose of using energy in the specific processes is therefore required.

To easily get a full overview of the entire facility pie charts and bar charts are made for each utility type at the site. As an example, an overview of the heating consumption for the given example is shown in Figure 8. These plots provide a good overview of the distribution of heat consumption for the entire site and make it easy to identify the main energy consumers at the site. In the example these are only created on site level, but for larger sites they can also be created on a production line level or section level, to have an even more detailed overview of where the energy is consumed. The overviews are created for each utility system at the site.

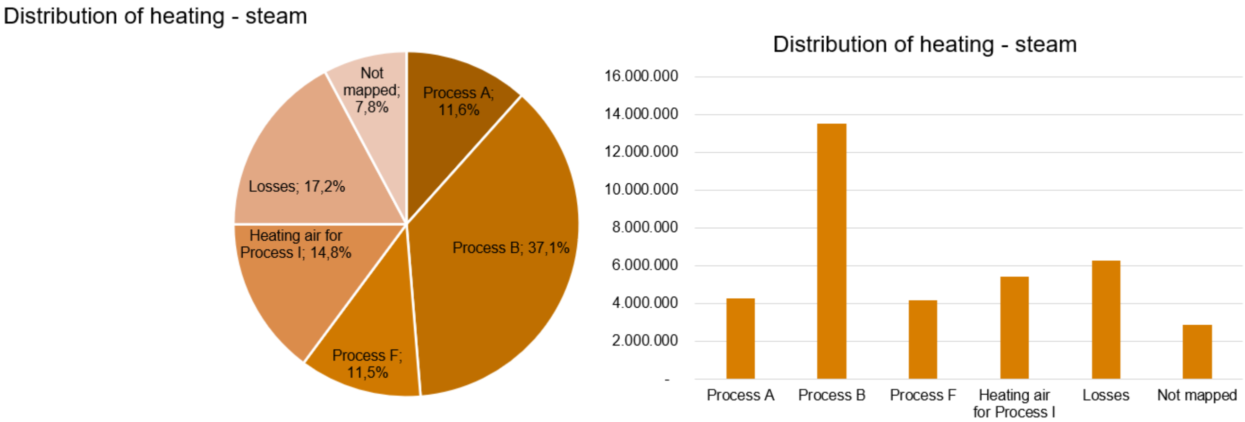


Figure 8: Charts for presenting the results of overall heat consumption. See Excel template sheet "Result Overview".

In addition to the overall overviews, it is often also useful to connect the consumption to temperature. This can help assess the potential for heat recovery and integration of, for example heat pumps. The graphs help give a good overview of what temperature levels the heating is utilized at. An example from the template is shown in Figure 9. Conclusions from these plots could for example be that:

- 80% of the heating is used for processes below 80°C (about 23 GWh) and all heating is below 100°C.
    - Can hot water be used instead of steam?
    - Any good heat sources for heat pumps?
- 20% of the cooling is used above 50°C (about 4 GWh).
    - Are there any potentials for heat recovery?

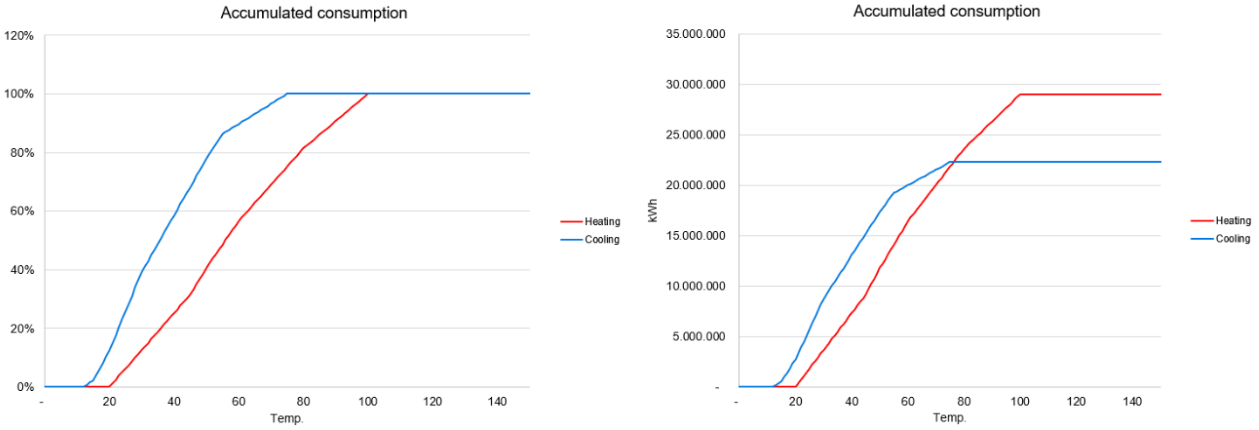


Figure 9: Accumulated thermal energy consumption. See Excel template sheet "Result Overview".

To gain a better overview of the relations between heating and cooling temperature levels, composite curves can be plotted for each. This is shown for the Excel template and in Figure 10 below, where the mapped waste heat streams have also been added. This analysis shows the amount of energy that is consumed at each degree of temperature. It can therefore be used to identify heat recovery potentials. The graph has four distinct areas.

- Orange area: theoretically minimum required heating utility
- Blue area: theoretically minimum required cooling utility
- Yellow area: Available waste heat from the processes
- Overlapping grey area: maximum potential for direct heat recovery between processes

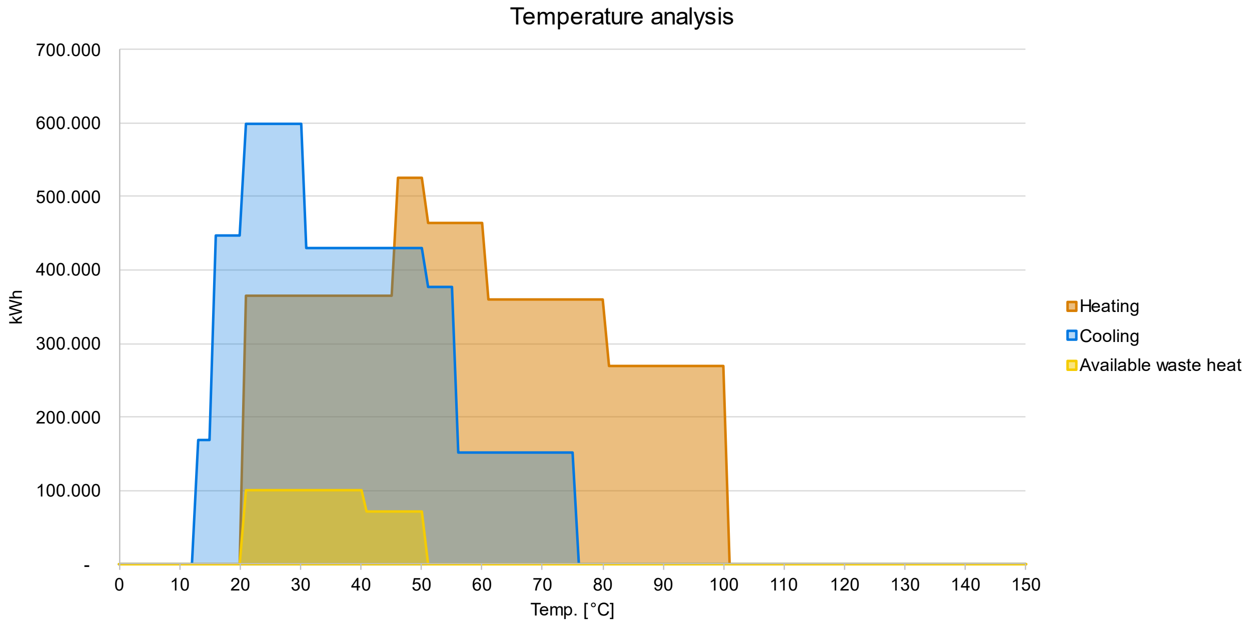


Figure 10: Example of a temperature analysis. See Excel template sheet "Result Overview".

In the example from the Excel template, it is seen that there is a high potential for implementing heat recovery between 20-75°C. Next step is to identify processes from the "Process mapping" tables with overlapping temperature requirements. In this example it can be seen that Process C for example can be matched with Process A and F:

Table 1: Potential heat recovery opportunities

Process	Temperature in [°C]	Temperature out [°C]	Energy consumption [MWh]
Process A	20	50	4.228
Process F	20	60	4.168
Process C	75	20	8.387

In terms of energy these streams almost match exactly, however, it will not be possible to cool Process C all the way to 20°C. A minimum temperature difference should therefore be introduced to reflect the physical limitations. Assuming a temperature difference of 5°C, this means that process C can be cooled to 25°C and that 7.627 MWh can be recovered for heating. Cooling and heating utility will therefore still have to be used in both ends.

It should be noted that the above exercise is fully theoretical. In the real world there are many more elements to consider when analysing the heat recovery potentials such as:

- **Matching operation times**: Are the processes running at the same time or are they batch controlled? Do we need a buffer tank?
- **Geographical location**: How far away are the processes from each other? Do the potential energy savings justify the piping investments?

It is therefore necessary to make a techno-economical analysis, estimating full investment costs and calculating payback times.

Once the energy consumption has been optimized, the utility system can should be evaluated. From the utility mapping sheet it should be evaluated whether the energy losses from the equipment can be minimized or recovered. In the Excel template, it is seen that waste heat from air compressors is already utilized in a 60°C hot water system. However, no heat is recovered from the chillers. There is a possibility to install an oil cooler or de-superheater on the chillers to supply more energy to the 60°C system. A lot of heat is also lost in the condensers of the chillers which could potentially be upgraded to higher temperatures with a heat pump. For the boilers it is seen that both boilers have an estimated flue gas loss of 5%. Recovering this in an economizer should therefore also be considered.

Appendix 2. Overview of types of heat exchangers

The simple overview of heat exchanger technologies presented below is taken from a Google-search and only aims at presenting an overview to be studied further in technical literature.

1. **Shell and Tube Heat Exchanger**:

- **Design**: Consists of a shell (outer vessel) and tubes (inner tubes).
- **Application Areas**:
  - Widely used in power plants, chemical processing, oil refineries, and HVAC systems.
  - Ideal for high-pressure and high-temperature applications.
- **Benefits**:
  - Efficient heat transfer due to large surface area.
  - Versatile design allows customization.
- **Limitations**:
  - Bulky and requires more space.
  - Prone to fouling and difficult to clean.

2. **Tube-in-Tube Heat Exchanger**:

- **Design**: Two concentric tubes with fluid flowing through the inner tube.
- **Application Areas**:
  - Used for pasteurization, food processing, and small-scale applications.
- **Benefits**:
  - Compact design.
  - Suitable for viscous fluids.
- **Limitations**:
  - Limited heat transfer area.
  - Not ideal for high-pressure applications.

3. **Double Pipe Heat Exchanger**:

- **Design**: Consists of two pipes (inner and outer) in parallel.
- **Application Areas**:
  - Commonly used for low-flow applications, such as laboratory setups.
- **Benefits**:
  - Simple construction.
  - Easy to maintain.
- **Limitations**:
  - Limited heat transfer capacity.
  - Inefficient for large-scale processes.

4. **Plate Heat Exchanger**:

- **Design**: Consists of stacked plates with alternating channels for hot and cold fluids.
- **Application Areas**:
  - Used in HVAC, refrigeration, and food industries.
- **Benefits**:
  - Compact and lightweight.
  - High heat transfer efficiency.
- **Limitations**:

- Prone to fouling.
- Limited to moderate pressures.

5. **Finned Heat Exchanger**:
   - **Design**: Metal fins attached to tubes or plates.
   - **Application Areas**:
     - Commonly used for air conditioning, automotive radiators, and electronics cooling.
   - **Benefits**:
     - Enhanced heat transfer due to increased surface area.
     - Suitable for gas-to-air applications.
   - **Limitations**:
     - Sensitive to fouling.
     - Complex maintenance.

6. **Adiabatic Heat Exchanger**:
   - **Design**: No heat exchange with the surroundings.
   - **Application Areas**:
     - Used in chemical reactors, where no heat is added or removed.
   - **Benefits**:
     - Maintains constant temperature.
     - No energy exchange.
   - **Limitations**:
     - Limited practical applications.
     - Requires precise control.

7. **Heat Exchangers with Built-In Cleaning Systems**:
   - These innovative heat exchangers incorporate mechanisms to maintain their efficiency by periodically cleaning themselves. Here are some notable examples:
     - **AX Cleaner®**:
       1. Developed by **AX System**, the AX Cleaner® is a semi-automated cleaning system.
       2. It uses a high-pressure water jet to effectively clean **air coolers** and **air condensers**.
       3. Designed to be lightweight, compact, and easy to maneuver.
       4. Minimizes risks to both the operator and equipment.
       5. Suitable for various installations, including A-frame or horizontal setups[1].
     - **Heat Exchanger Tube Cleaning System**:
       1. Utilizes **Schmitz Cleaning Balls** injected into the heat exchanger cooling water.
       2. The cleaning balls pass through the tubes, effectively cleaning the inner tube surface.
       3. Ideal for maintaining heat exchangers in process tanks[2].
     - **Self-Cleaning Heat Exchangers**:
       1. Based on a fluidized bed of particles circulating through the tubes of a vertical shell-and-tube exchanger.
       2. Provides continuous cleaning action, reducing fouling and improving efficiency[3].

8. **Corrosion-Resistant Heat Exchangers**:
    - Corrosion can significantly impact heat exchanger performance and lifespan. Here are some materials and designs used to combat corrosion:
        - **Stainless Steel**:
            1. Widely used due to its excellent resistance to corrosion in various applications.
            2. Suitable for heat exchangers handling aggressive media[4].
        - **Silicon Carbide Heat Exchangers**:
            1. All wetted parts are made of **PFA**, **FFKM**, and **silicon carbide**.
            2. Ready to handle almost any very corrosive and toxic chemicals.
            3. Ideal for conveying abrasive chemical solutions[5].
        - **Graphite Plate Heat Exchangers**:
            1. Assembled with **Diabon graphite plates** for near-universal chemical compatibility.
            2. Highly resistant to hydrochloric, phosphoric, and hydrofluoric acids.
            3. Suitable for aggressive media[6].
        - **Plastic Heat Exchangers (CALORPLAST)**:
            1. CALORPLAST offers plastic immersion-type, gas-liquid, shell and tube, tube plate, and gas-gas heat exchangers.
            2. Designed for critical media, including highly concentrated inorganic acids and aggressive substances.
            3. Ensures longevity, efficiency, and sustainability in corrosive environments[7].

The choice of heat exchanger depends on factors like fluid properties, operating conditions, and space availability. Each type has its advantages and limitations, so engineers must carefully consider these aspects when designing industrial processes[1][2][3].