IEA SHC Task 49 **SolarPACES Annex IV**

Solar Process Heat for Production and Advanced Applications

Integration Guideline

Guideline for solar planners, energy consultants and process engineers giving a general procedure to integrate solar heat into industrial processes by identifying and ranking suitable integration points and solar thermal system concepts.

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Contents

Definitions and Nomenclature

Collector loop: All necessary components to convert solar irradiance into heat and to transfer this heat via the collector fluid to the next heat transfer point.

Direct solar heat integration: Solar heat integration without a heat exchanger (process medium or heat transfer fluid heated within solar thermal system).

Heat transfer fluid (HTF): Medium delivering heat to the process (e.g., hot water, steam, thermal oil). The heat transfer medium might deliver the heat indirectly (via heat exchangers) or directly (e.g., direct steam injection).

Indirect solar heat integration: Solar heat integration via heat exchanger.

Industrial heat supply and distribution network: Complete thermal system of an industrial or commercial production site (including heat generation, heat transfer, heat storages, heat recovery, heat transfer to processes, etc.).

Integration point: An integration point specifies a heating demand within an industrial or commercial plant that can be (partly) supplied by solar heat (e.g., heating of boiler make-up water; heating of a process medium). The term "point" is used instead of unit operation or sink to highlight the fact that some sinks could be supplied by various heat exchangers and at different temperature levels.

Integration return temperature: Return temperature from the integration point to the solar thermal system. The integration return temperature can be constant (e.g., when cold water from the grid is heated) or varying (e.g., at return flow boost of a heating network with varying thermal load).

Integration flow temperature: Solar supply temperature to the integration point. Depending on the integration requirements, a maximum, minimum or set temperature level has to be provided and the solar thermal system concept has to be selected accordingly.

Process flow temperature: Heat exchanger outlet temperature on process side. This temperature specifies the heat supply temperature to the process and may differ from the process temperature.

Process return temperature: Heat exchanger inlet temperature on process side. This can be either a return flow from a process or fresh water from the tap.

ΔT: Temperature lift in heat exchanger on process side.

Process temperature: Temperature of the process medium during the process operation. The process temperature can change during processing (e.g., in gradual heating processes).

System utilization ratio: Ratio between solar thermal energy transferred to the supported processes and the solar irradiance onto the collector aperture area. Typically, annual values are given and as a synonym sometimes the term "annual system efficiency" is used.

Load profile: Daily, weekly, and annual heating power demand of an integration point over time. Mathematical integration of this load profile gives the annual heat demand of the integration point in kWh.

Process: A process is a set of real activities (e.g. a sequence of unit operations) performed by people and machines that produce an outcome (a product or an intermediate product) (based on IPAPI, 2014).

Process level: All operations done at the level of processing, including heat transfer to unit operations, in contrast to “supply level” which includes generation and distribution of heat.

Process integration: Systematic and general methods for designing integrated production systems, ranging from individual processes to total sites, with special emphasis on the efficient use of energy and reduction of environmental effects (Gunderson, 2000).

Process intensification: PI is characterized by radically innovative principles (“paradigm shifts”) in process and equipment design, which can bring significant benefits in terms of process and chain efficiency, capital and operating expenses, quality, wastes, process safety, etc. (Gorak and Stankiewicz, 2012). An all-embracing definition is: ‘Any engineering development that leads to a substantially smaller, cleaner, safer, and more energy efficient technology is process intensification’ (Stankiewicz and Moulijn, 2004; Reay, 2008).

Process medium: In some processes the product is heated via an intermediate process medium, which again is heated by a central heat transfer medium (e.g., cooking of meat in a hot water bath, which is heated via steam).

Process optimization: An action or activity taken on a process that improves its efficiency in respect to the intended outcome of the process (IPAPI, 2014).

Product: The processed material (feed, product, intermediate product) being treated in the process (e.g., distilled fluid in distillation; milk in cheese fermentation, etc.).

Solar fraction: Share of the overall demand of the thermal loads connected to a solar heating system, which is supplied by solar heat.

Solar heat: Thermal energy that has been generated by solar thermal collectors from the conversion of solar irradiance.

Solar heating system: All components that are necessary for solar heat supply, including collector loop, storage, storage charging and discharging devices, as well as the integration heat exchanger.

Solar heat integration: Supply of solar heat to a given integration point within a production line. The heat sink can be located at process level or supply level.

Solar heat integration concept: A solar heat integration concept for a certain integration point depicts by which heat exchanger and hydraulic connection solar heat can be transferred to a process based on the existing heat supply technology (e.g., direct steam supply, hot water or air supply via external heat exchanger, hot water or air supply via internal heat exchanger, etc.).

Solar process heat system concept (SHIP system concept): The SHIP system concept describe the whole technical concept of the solar thermal process heating system including the solar heat integration concept. Thus, they build upon the solar heat integration concepts and additionally include all components of the SHIP system.

Supply level: All operations done for generation and distribution of heat.

Unit operation: A unit operation is any part of a potentially multiple-step process which can be considered to have a single function (Wikibooks, 2014). "Any chemical process, on whatever scale conducted, may be resolved into a coordinate series of what may be termed 'unit operations', as pulverizing, dyeing, roasting, crystallizing, filtering, evaporation, electrolyzing and so on. The number of these basic unit operations is not large and relatively few of them are involved in any particular process. The complexity of chemical engineering results from the variety of conditions as to temperature, pressure etc., under which the unit operations must be carried out in different processes, and from the limitations as to material of construction and design of apparatus imposed by the physical and chemical character of the reacting substances." (Little, A. D., 1916).

Abbreviations:

BAT	Best Available Technologies
BREF	Best Available Techniques Reference
CC	Composite Curve
CHP	Combined Heat and Power
COP	Coefficient of Performance
CP	Cleaner Production
EE	Eco Efficiency
EE	End Energy
EL	Extra Light
GCC	Grand Composite Curve
HEX	Heat Exchanger
HR	Hear Recovery
HTF	Heat Transfer Fluid
LPG	Liquefied Petroleum Gas
NE	Useful Energy
ODEX	Energy Efficiency Index
ORC	Organic Rankine Cycles
PCM	Phase Change Material
PE	Primary Energy
PI	Process Intensification
RE	Renewable Energy
SEC	Specific Energy Consumption

SHIP	Solar Heating for Industrial Processes
UHT	Ultra High Temperature
UO	Unit Operation

1 How to Use this Guideline

Bettina Muster

When integrating solar heat into industrial or commercial processes, the aim is to identify the most technically and economically suitable integration point and the most suitable integration concept. Due to the complexity of heat supply and distribution in industry, where a large number of processes might require thermal energy, this task is usually not trivial. This document provides guidance for planners of solar thermal process heat systems (SHIP), energy consultants and process engineers. It describes a general procedure for the integration of solar heat into industrial processes, including the necessary steps to identify suitable integration points for SHIP and integration concepts. Based on these concepts, SHIP system concepts are given. The document can be used as supporting material in solar process heat trainings of planners, energy managers and consultants, or as additional help for energy experts besides their own practical experiences. *The scope of this document does not include a description of detailed planning steps of the solar thermal system itself.*

Integrating solar heat is possible at several points in the heat supply and distribution network of an industrial production site (see Figure 1-1). Chapter 2 therefore gives an overview on heat supply and distribution in industry starting with a short description of conventional heating equipment and distribution media. On the process level, basically the existing heat transfer concepts (e.g., type of heat exchanger and control strategies) are decisive on how solar heat can be integrated into the processes. Therefore, the basic existing heat transfer concepts in industry are explained. It is shown that the variety of different thermal processes re-occurring in industry can be classified based on the unit operation concepts, specifying suitable integration concepts and solar process heat system concepts (introduced and explained in later chapters) per unit operation. This has been and will further be realized in the online wiki-web database "Matrix of Indicators" (available online), which is an information portal (among others) for solar thermal integration.

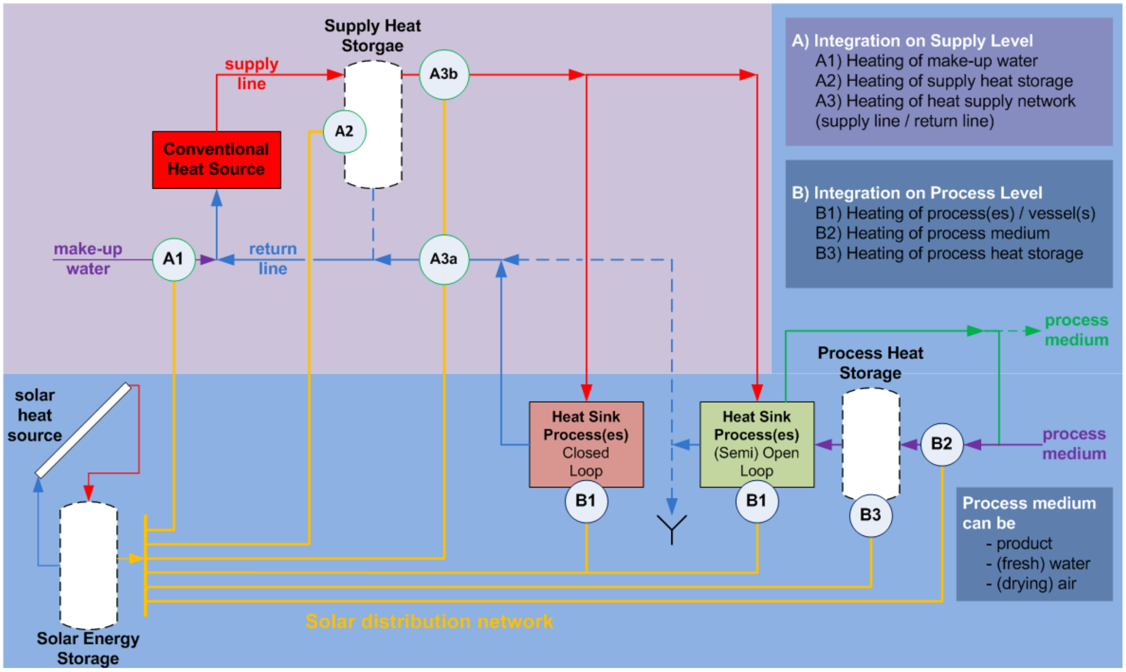

Figure 1-1: Possible integration points for solar process heat (AEE INTEC, 2012)

After summarizing some basics on heat supply and distribution networks in Chapter 2, Chapter 3 introduces the "Assessment methodology for solar thermal integration," which was defined in IEA SHC Task 49. This methodology builds upon existing strategies (e.g., IEA SHC Task 33) and summarizes the most important steps for planning a solar process heating system. These steps include a pre-feasibility study (steps 1-2), company visit (step 3), analysis of status quo (step 4), energy efficiency considerations (step 5), and identification of integration points (step 6). And for planning a SHIP system, the analysis of the chosen suitable integration points (step 7) and solar integration concepts (for one or several integration points) are economically and energetically compared based on technical and economic considerations. At this point, a basic design of the solar thermal system(s) is necessary in order to evaluate an optimum cost/benefit - ratio, including the definition of an appropriate collector field size, the storage volume and the type of solar thermal collectors used. After the decision (step 8) is taken based on this comparative analysis, the detailed planning begins (step 9). *As highlighted above, the scope of this document only includes the steps 1-7. Details on solar thermal system design will be given elsewhere (reference to IEA SHC Task 49 Handbook).*

Chapter 4 is dedicated to energy efficiency considerations in industry and shows how process integration can be used as a basis for identifying possible integration points (see Chapter 6) for solar thermal systems.

In Chapter 5, concepts for SHIP integration are explained and classified into supply and process level. On supply level the classification is based on the existing heat transfer medium, whereas on process level the basis for classification is the heat transfer technology (type of heat exchanger etc.). The integration concepts show how solar heat can be integrated to the industrial supply network or process(es).

Chapter 6 builds upon these concepts further showing how they can be extended to complete solar process heat system concepts. Hydraulic schemes with details on collector field and loop, buffer storage, as well as on the overall control strategy (e.g., charging and discharging strategies) are given. A selection matrix shows how suitable SHIP system concepts and integration concepts are interlinked.

Chapter 7 discusses how suitable integration points can be identified and prioritized. This Chapter builds upon data acquired in the analysis of status quo and/or in the efficiency considerations (see Chapter 4) and on the possible solar integration concepts taken into account, as their specifications may influence the suitability of one integration point over another.

2 Thermal Processes and Heat Distribution Networks in Industry

Bettina Muster, Bastian Schmitt, Hans Schnitzer

Highlights

- The layout of the existing processes and heat supply is pivotal for the solar thermal system design.
- The existing heat supply in industry relies on a few common conversion technologies with steam and hot water networks for distribution.
- The unit operation approach enables systematic overview of solar heat integration possibilities for thermal processes in industry.
- Heat transfer equipment in industry can be classified by type of heat exchanger and heat pump.
- Industrial relevant cold supply technologies are compression chillers and potentially absorption chillers.

The aim of this chapter is to give an overview of the existing thermal processes, heat supplies, and distribution systems in industry. As solar thermal systems are typically integrated into existing industrial sites, the layout of the existing processes and heat supply is pivotal for the integration possibilities. The chapter first summarizes heat generation systems before showing a schematic of different processes by the concept of unit operations. Also, future trends in industrial processing are indicated.

The various types of heat exchangers that exist in industry can be used to classify current heat supply strategies. Heat pumps give value to low temperature waste heat, which is widely available in industry. Finally a short overview on industrial cooling processes is given.

2.1 Conventional Heat Generation Systems in Industry

The design of heat supply systems in industry is primarily influenced by the fuel being used and the heat transfer fluid (HTF) (e.g., thermal oil, superheated steam, saturated steam, pressurized hot water, air). While in some parts of the world coal is still the primary energy source, European and North American industries rely mainly on gas, LPG, and oil. Biomass is still used widely in countries such as India, where there is less access to oil and gas, and is increasingly becoming interesting for industrial countries as a renewable energy source. With the trend towards renewable energy integration, biogas also plays a role, specifically in industrial sectors with potential to produce biogas from their waste products and wastewater. Additionally, several thermal processes are heated electrically and cooling is mainly provided by electricity, with absorption cooling playing rather a minor role today, but increasingly being investigated. Finally, the growing number of district heat networks allows industries to directly heat their processes using externally produced heat.

All the mentioned fuels require an energy conversion plant on-site to produce thermal energy, with direct electrically heated processes and processes supplied via district heating being the only exceptions. In Table 2-1 typical conversion technologies for the most common HTF in use are shown. Obviously, boilers differ substantially in their design depending on the fuel being used (e.g., a gas boiler differs largely from a solid fuel (coal/biomass) boiler). Important parameters of the different boiler types are in their start-up and shutdown times as well as the time needed to adjust the heating power supply to demand variations in different configurations. Boilers for solid fuels require much longer times for starting and shutting down, therefore their reaction time to load changes is much longer. This leads to heat storages often being employed in such systems. Liquid fuel boilers and burners on the other hand can react quickly to load changes and can be controlled easily within a large range of load variations.

Table 2-1: Thermal energy conversion technologies

Conversion Technology	Fuel	Heat Transfer Fluid
Boiler	Gas, LPG, oil, coal, biomass, biogas (also in combination with natural gas)	Steam, hot water, thermal oil
Cogeneration systems	Gas, LPG, oil, coal, biomass, biogas (also in combination with natural gas)	Steam, hot water, thermal oil
Burner	Gas, LPG, oil, coal, biomass, biogas (also in combination with natural gas)	Hot air
Heat pump	Electricity	Hot water, hot air, thermal oil

The choice of the conversion equipment is based on the choice of the heat distribution medium. In most industries the distribution medium is steam or (pressurized) hot water, therefore mainly boilers or cogeneration systems (typically in larger plants for efficient production of electricity and heat) are in use. Steam boilers are in several aspects more complex than hot water boilers, as the steam-condensate cycle requires more care and handling steps than hot water systems (water treatment, condensate recovery, and degasification). Large plants require specifically trained personnel. In particular, open condensate systems may lead to water losses and significant energy losses if not handled with care. However, many plant operators choose steam, as it is advantageous for its high energy density, enabling small distribution tube diameters and high heat transfer rates, ensuring a constant temperature due to condensation. Additionally, steam systems are often the traditional way of heat supply. Hot water systems are easy to operate and maintain, but do require large distribution pipe diameters and heat transfer areas (in comparison to steam). When temperatures above 100 °C are required, water systems also require pressurization. Thermal oil or silicon oil are other alternatives that can be operated at lower pressures than water for a given temperature, as their evaporation temperatures can be up to 300 °C, but comes lower specific heat capacities and higher costs. Silicone oil is often used in cogeneration systems, such as Organic Rankine Cycles operated between 200 to 300 °C. Finally, air can be used as a HTF; however, due to its comparably low heat capacity per volume, hot air is usually not used exclusively as a heat distribution medium, but rather heated locally at the processes requiring hot air (such as drying). In plants where the only significant heat demand is for convective drying (e.g., tea factories, malting plants) a hot air burner might be the main heat supply device.

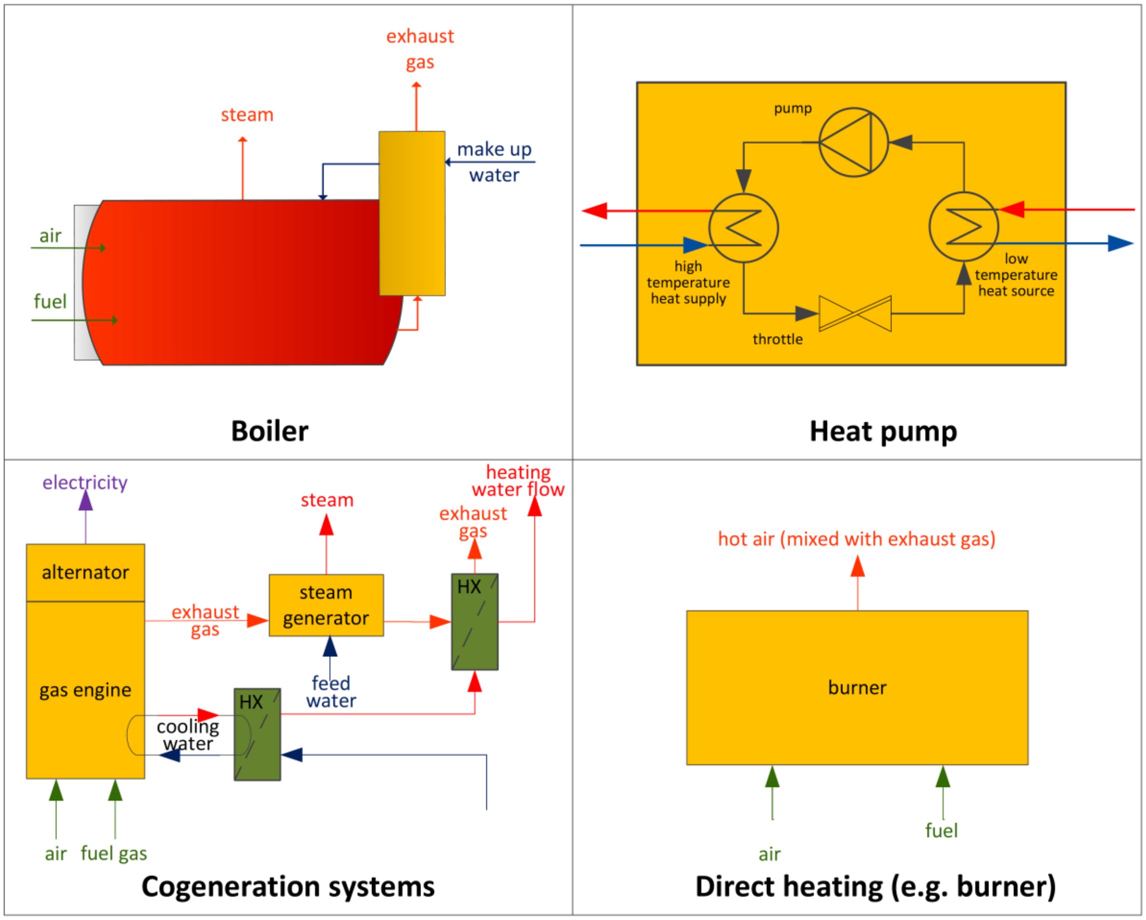

Figure 2-1: Schemes of conversion technologies with basic components

Thermal storages are a crucial aspect in many industrial heating systems. Basically, we can differentiate between storages being integrated in the energy distribution and supply system, and storages that are integrated on the process level, where process media are stored (see Figure 1-1). Within the supply and distribution systems, the main aspect of thermal energy storages is to keep the boiler/burner load at a rather constant level. Therefore storages are placed primarily in systems with slow reacting energy supply systems, such as biomass or coal boilers. Typically, hot water storages (pressurized or non-pressurized) are used, with steam storages being the exception. This stems from the fact that most steam boilers in industrialized countries are operated by natural gas, LPG, or oil, and load changes can easily be matched by these types of boilers. In steam systems operated with coal boilers, the storages are used more commonly to level off fluctuating demands. New storage concepts, such as latent and thermo-chemical heat storage, currently play an insignificant role in the existing heat systems in industry, but do have potential for some specific applications.

It is possible to integrate solar heat in all types of supply and distribution networks mentioned above. However, for each type of network only specific integration concepts and solar thermal system designs are possible (see Chapters 5 and 6).

2.2 Frequent Thermal Unit Operations

In industry, a broad range of processes exist. However, they are made up of a relatively few single process steps that repeat themselves. In order to classify these different steps, the concept of unit operations, introduced already in 1905 by Arthur D. Little, has been established. The basic idea of the concept is to classify operation steps with similar physical laws into one “unit operation” (Prakashan, 2009). There are classes of unit operations, such as heat transfer, mass transfer, fluid flow, and mechanical operations based on the basic operating principle (Prakashan, 2009). In heat transfer operations, the basic principle is transferring heat (based on a temperature gradient), while mass transfer operations rely on the mechanisms of molecular diffusion. For describing processes in industry with thermal energy demand, mainly heat transfer operations (e.g., heating, cooling, evaporation, drying, or distillation) and mass transfer operations (e.g., extraction, absorption, distillation, drying, or crystallization), are relevant classes of unit operations (Prakashan, 2009). Obviously some operations, such as distillation or drying, fall into both classes. As there is not always a clear distinction into which category one operation falls, the categorization of unit operations used by different authors is not always completely consistent.

Most importantly, for integrating solar heat in industry, the concept can be used as a good overview of the list of unit operations in different industry sectors showing their implementation possibilities for solar heat. The wiki-web “Matrix of Indicators”, hosted by the Technical University of Graz, is a database of unit operations in industry that has been established as an information source on solar process heat within IEA SHC Task 33 (http://wiki.zero-emissions.at). The database provides a general description of each unit operation and shows possible solar integration schemes[1]. Furthermore, a sub-matrix exists for each industry sector that shows more details on the processes. By clicking on a process icon, information, such as temperature and energy demand, and a typical process layout can be found. In addition, energy efficiency measures and alternatives to conventional technologies are described and case studies on solar thermal integration are included.

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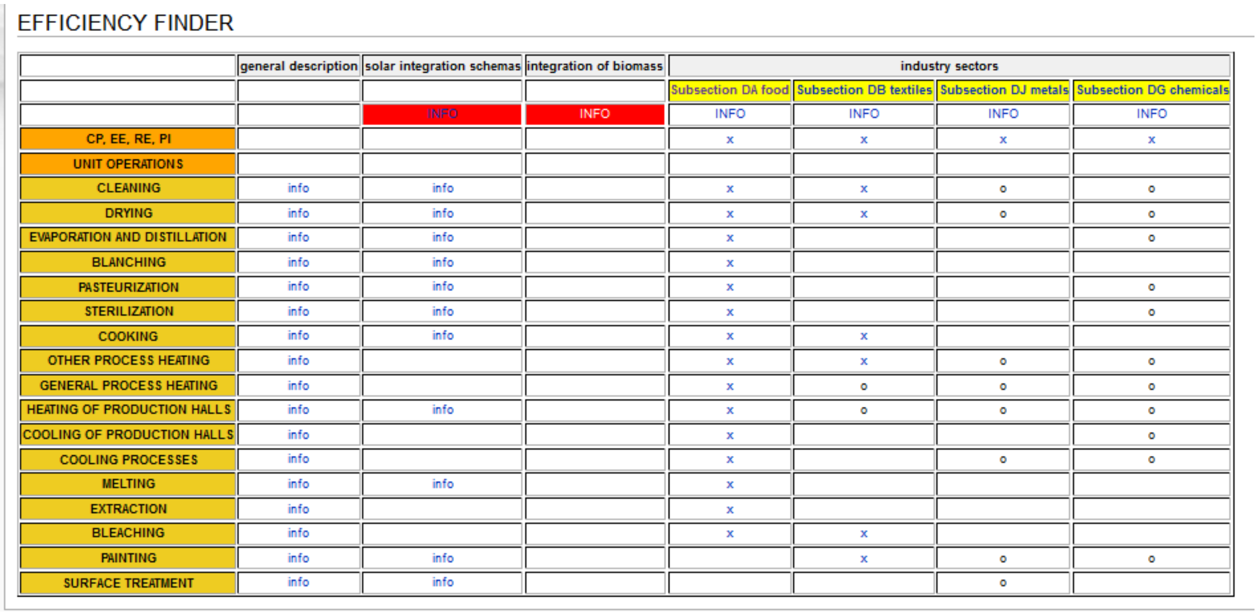
[1] It is foreseen to integrate the newly elaborated solar integration schemes (see Chapters 5 and 6 of this guideline) into the Matrix. However, this will only happen step by step in the future, and dependent on financing possibilities (e.g. for the food industry, the Matrix will be extended within the project Greenfoods).

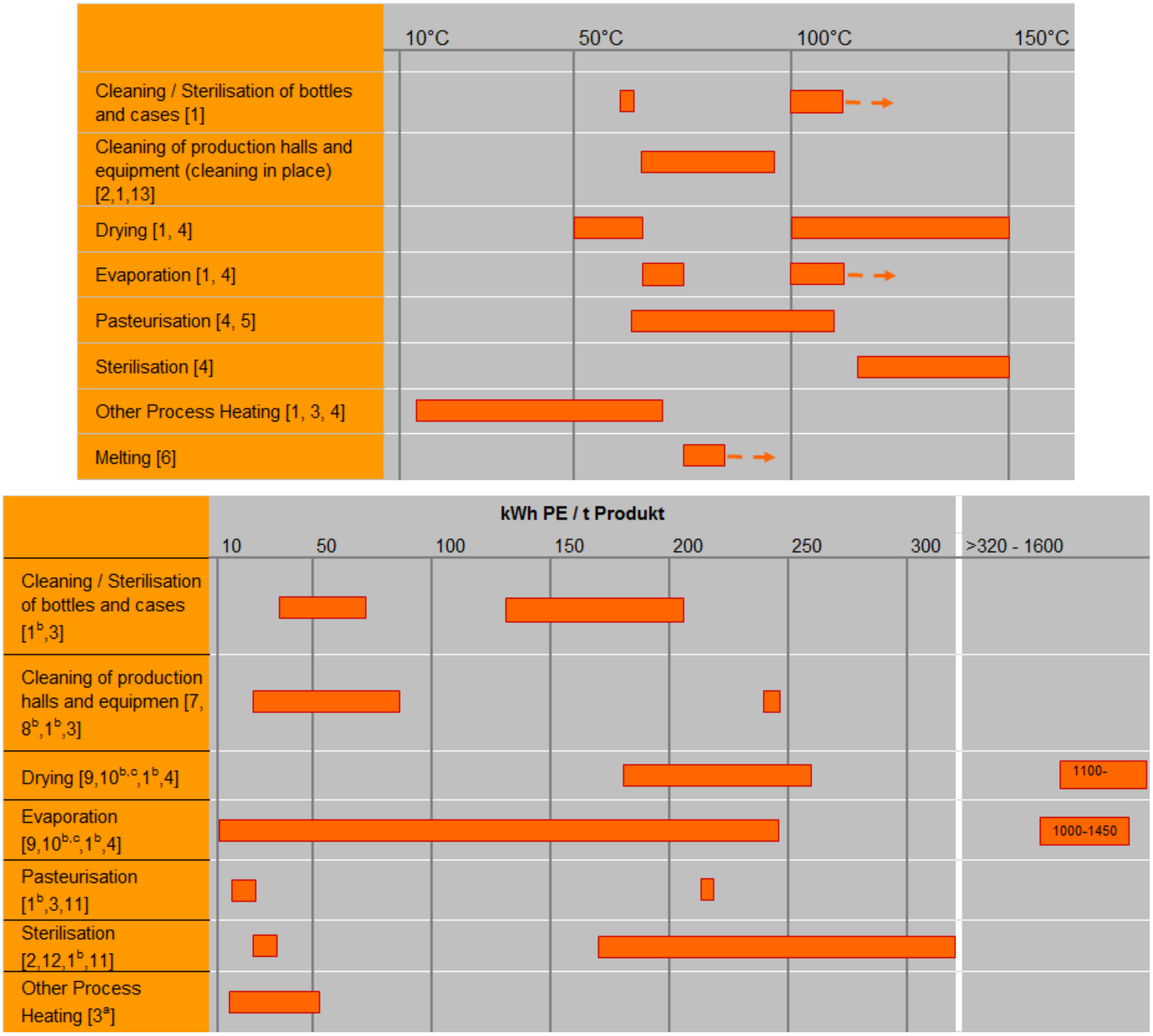


EFFICIENCY FINDER

	general description	solar integration schemas	integration of biomass	industry sectors			
				Subsection DA food	Subsection DB textiles	Subsection DJ metals	Subsection DG chemicals
		INFO	INFO	INFO	INFO	INFO	INFO
CP, EE, RE, PI				x	x	x	x
UNIT OPERATIONS							
CLEANING	info	info		x	x	o	o
DRYING	info	info		x	x	o	o
EVAPORATION AND DISTILLATION	info	info		x			o
BLANCHING	info	info		x			
PASTEURIZATION	info	info		x			o
STERILIZATION	info	info		x			o
COOKING	info	info		x	x		
OTHER PROCESS HEATING	info			x	x	o	o
GENERAL PROCESS HEATING	info			x	o	o	o
HEATING OF PRODUCTION HALLS	info	info		x	o	o	o
COOLING OF PRODUCTION HALLS	info			x			o
COOLING PROCESSES	info			x		o	o
MELTING	info	info		x			
EXTRACTION	info			x			
BLEACHING	info			x	x		
PAINTING	info	info			x	o	o
SURFACE TREATMENT	info	info				o	

Figure 2-2: Main page of the „Efficiency Finder“ (http://wiki.zero-emissions.at)

To evaluate the potential for solar thermal energy, a basic knowledge on energy demand and required temperatures of the processes is crucial. Therefore, there has been a focus on compiling typical heat demand and temperature ranges for the most important processes in different industry sectors. Within the project Solarfoods (www.solarfoods.at), for example, specific data on primary energy demand and temperature levels in the food industry were compiled for all processes of each subsector in the food industry with relevant thermal energy demand. Such information tables (see Figure 2-3 and **Fehler! Verweisquelle konnte nicht gefunden werden.** for dairy examples) are helpful for giving an overview on how much energy is required at what temperature level, which is also basic information required for solar thermal system design (see Chapter 6). In the future, this type of information table for a certain subsector will be included in the wiki-web “Matrix of Indicators” when the data is available. Such general information on one subsector can be found in the matrix by clicking on the INFO button of the respective subsector.



Two bars signify that depending on the technology the process may run at two different temperature levels
a) initial data in NE, conversion factor NE to EE: 80 % boiler efficiency and EE to PE: PE-factor for natural gas and heating oil EL = 1,17 (Theissing, 2010)
b) initial data in EE, conversion factor EE to PE: PE-factor for natural gas and heating oil EL = 1,17 (Theissing, 2010)
c) data from Dutch Dairy Statistics (http://www.prodzuivel.nl/): data in specific energy consumption (SEC) of fuel and heat – estimation of EE
[1] Karagiorgas, M. & Botzios-Valaskakis, A., Solar systems applications in the dairy industry, Center for Renewable Energy Sources (CRES), Greece.
[2] Hogaas, E., 2002, cited in: Ramirez et al., 2006
[3] Bayerisches Landesamt für Umweltschutz, 2000, Minderung öko- und klimaschädigender Abgase aus industriellen Anlagen durch rationelle Energienutzung – Milchverarbeitender Betrieb.
[4] Ramirez, C.A., Patel, M. & Blok, K., 2006a, From fluid milk to milk powder: Energy use and energy efficiency in the European dairy industry, Energy 31, 1984-2004.
[5] Goff, D., 2011, Dairy Science and Technology Education, University of Guelph, Canada, [www.foodsci.uoguelph.ca/dairyedu/home.html], last accessed 11.05.2011.
[6] European Commission, 2006, Reference Document on Best Available Techniques in the Food, Drink and Milk Industries.
[7] Arcadis IMD, 2002a, cited in: [11] Xu & Flapper, 2009.
[8] Natural Resources Canada (NRCAN), 2001 cited in: [11] Xu & Flapper, 2009.
[9] Arcadis IMD, 2002b cited in: [14] Ramirez et al., 2006a.
[10] Ramirez, C.A., Blok, K., Neelis, M. & Patel, M., 2006b, Adding apples and oranges: The monitoring of energy efficiency in the Dutch food industry, Energy Policy 34, 1720-1735.
[11] Hvid, J., 1992, cited in: Ramirez et al., 2006a.
[12] National Dairy Council of Canada, 2001 cited in: Ramirez et al., 2006a.
[11] Xu, T. & Flapper, J., 2009, Energy use and implications for efficiency strategies in global fluid-milk processing industry, Energy Policy 37, 5334-5341

Figure 2-3: Temperature levels of unit operations and primary energy demand of unit operations in the milk processing industry (Brunner et al., 2012)

2.3 Future Trends in Process Design and Effects on Solar Process Heating

The industrial process layout is the key for designing an efficient energy supply, whether a boiler will cover the demand or whether a solar process heat plant will be integrated into the energy supply. Although some industry sectors tend to maintain old practices and are reluctant to change, there are steady and on-going developments in the processing industries towards more efficient processes with high quality products. A large number of optimization approaches and new technological developments can be summarized by the umbrella term “Process Intensification”.

In process engineering, research on “intensifying” industrial processes has increased tremendously in the past years, mainly in the chemical and pharmaceutical industries, but in other sectors as well. Various studies demonstrate the potential for new process system designs achieving higher process efficiencies. These new process technologies will often require different energy supplies compared to the conventional technologies in use. It is therefore important to keep in mind which intensification strategies might have an effect on the possibilities to integrate solar thermal heat. In the following, several strategies that might affect energy supply possibilities are mentioned. In the long run, it is the aim to integrate examples of new technological solutions for different processes more specifically in the wiki-web “Matrix of Indicators”.

Process Intensification ususally aims at higher productivity with smaller equipment (such as compact heat exchangers or micro reactors). The target is to increase product yield at constant raw material input and decreasing by-products, while maintaining or decreasing energy input. This is in many cases achieved by an increase in mass and/or heat transfer. This might be realised by several means, e.g. by making use of the synergistic effect of reaction and separation (e.g. membrane processes) and by combinations of unit operations. Further examples can be found at www.pinetwork.org or specific literature (Reay et al, 2013).

Mass and heat transfer phenomena are often interdependent: in processes limited by heat transfer, mass transfer can be enhanced once the heat transfer limitation is overcome. Vice versa, processes may run at lower temperatures when a physical change of the process design increases mass transfer rates (e.g. change from evaporation to a membrane based process). This might allow one to integrate a different energy supply. Obviously, all these intensification strategies that influence heat transfer rates and/or change the heat supply of the processes, might affect the solar process heat potential. Another important aspect for designing new energy supply systems is the variability of process energy demand. This can be again linked with mass and heat transfer rates, as the change from a batch reactor to a continuous reactors leads in many cases to mass and heat transfer improvements. The change from batch to continuous processes is an important intensification strategy for solar thermal integration (Muster and Brunner, 2015). Due to the elimination of peaks in heating/cooling demand a change towards continuous process heat demand has a large effect on energy supply and its design. Heat storages are common in industry to overcome time variations in heat supply and heat demand, be it for heat recovery systems or for efficient integration of energy supply technologies. Also in many cases the solar process heat system design will include heat storages. This is, in itself, an opportunity to intensify heat stores via, for example, enhanced heat transfer surfaces.

Intensification strategies that will affect the potential for solar thermal integration are obviously those that overcome heat transfer limitations. In general, there are several strategies to either increase the heat transfer rate or to overcome heat transfer limitations (Muster and Brunner, 2015):

- Increase of heat transfer area (e.g. compact heat exchangers),
- Increase of heat transfer coefficient (e.g. reactors with new flow regimes, such as spinning discs - and while this needs an electrical energy input, this could be potentially generated by solar photovoltaics),
- Lower the process temperatures by optimized process system design and/or by changing feedstock formulations, or
- Switch to an energy supply without thermal gradients (e.g. microwave heating - again needing an additional electrical energy input).

These can usually, at least to some extent, be integrated into an existing plant. Retrofit changes are naturally limited by the availability of space and/or the existing infrastructure (e.g., control system, etc.). A change in technology will of course increase possibilities for enhancements to a high extent.

Such a change in technology is necessary when changing the physical process phenomenon. Changes that affect the integration of energy supply possibilities, such as solar heat, include (Muster and Brunner, 2015):

- Increased selectivity of separation processes (e.g. change from atmospheric evaporation to membrane assisted processes)
- Electromagnetic action on molecules and microorganisms (e.g. change from thermal inactivation of microorganisms to non-thermal techniques, such as microwave or pulsed electric field)
- Enhanced thermal storage (and its control) to meet the demands of compact and responsive stores able to match continuous process demands.

Within IEA SHC Task 49, an expert meeting of process engineers and solar engineers was conducted to discuss the possible effects of new trends in processing on future energy supply. The experts expect, based on the discussions that energy supply will change by the impact of new developments (PI) to the processing industries. These effects will be visible on three levels: the unit operation level, the plant level, and the region level through new general processing approaches. While there will be a shift from thermal processes to (at least partly) electrically driven processes on the unit operation level, heat supply will remain an important aspect and there will be a trend to lower processing temperatures brought about by continuous processing and new catalysts, enzymes or alternative chemical reaction pathways. On the plant level, plant intensification should lead to integrated production sites in which thermal energy is (re-) used at its best and energy conversion losses are minimized. It will be an ongoing challenge to realize production sites in which intensification is achieved in such way that process efficiencies are at maximum while the overall plant energy requirement reaches a minimum. The major impact besides a changing energy requirement of unit operations and on plant level is, however, the general approach in processing, whether bulk processing will remain the way to go or whether there is a trend towards distributed small-scale processing. This would enable more flexibility and faster reactions to energy supply variations.

For solar process heat, a few specific trends can be indicated:

- Flexible small scale processing can increase the solar yield for heating industrial processes, when the process regulation can follow the availability of solar heat. Additionally there is a huge potential to access the available heat in summer and if necessary store it for the winter with new storage concepts.
- Most new energy conversion technologies require a drying step for which solar drying technologies would contribute to the increase of efficiency of the overall conversion process. (This competes with vapor recompression systems; however this heat might be used for other processes at higher temperature levels.)
- The further implementation of advanced heat recovery systems (covering a large share of low temperature heat demand in industry) will increase the demand for solar process heat in the higher temperature range, thus proving the importance for research in collector technology for a temperature range of 100 to 250 °C.
- The shift to electrically driven processes however will eliminate current waste heat streams. Studies on the holistic picture of plant intensification and energy supply will be important to realize sustainable processing sites in the future.

2.4 Heat Supply of Processes

The different thermal processes in industry are conventionally heated using a few basic heating strategies. Conventional heat delivery to industrial processes using internal or external heat exchangers as well as direct steam injection are especially important for the substitution of fossil fuels for solar thermal energy. Besides these technologies, evaporators and dryers are of high relevance. These installations can be found in almost every industry sector.

2.4.1 Heat exchanger types in industry

Below is some general information on the different types of heat exchangers. The aim of this section is not to provide detailed information on heat exchanger (HEX) types, but rather to show how heat exchangers can be classified. This classification is later used in Chapter 5. For more information on heat exchanger types and details refer to the specific literature on this subject, such as (VDI, 2013; Holman, 2002). Basically, we can distinguish between external heat exchangers placed outside a process bath/vessel/machinery or internal heat exchangers placed inside a process bath/vessel/machinery.

Different types of **external heat exchangers** are used to heat industrial processes. A suitable HEX type is chosen according to the applied temperature and pressure, phase change, available space, or specific properties of the heated media such as viscosity and corrosiveness (VDI GVC, 2006). According to (Shah et al., 2003), the most important types are tubular-, compact-, and extended surface HEX.

Tubular HEX is the most common type of heat exchangers in industry and cover tube bundle- and double pipe HEX. Tubular HEX is made of a closed tubular jacket that encloses a bundle of tubes. This creates a shell space that is encircled by a medium. The other medium flows through the tube bundle, which consists of plain or ribbed tubes (Vauck and Müller, 1988).

Compact HEX cover plate- and spiral HEX are suitable for media with different viscosity. The most common compact HEX type is the plate heat exchanger. Within the food industry, sealed plate heat exchangers are often used. The plates typically have strong profiles and are held together by clamping screws and frames. Spiral HEX consists of two equal-width steel strips that are spirally wound at an equal distance to an axis. The resulting channels are closed at both ends by removable covers with gaskets. These HEX types are mainly used for liquid-liquid applications, condensation, or gas cooling (Shah et al., 2003; VDI GVC, 2006).

For applications where one of the media has a much lower heat capacity (e.g., water-air), extended surface heat exchangers are used. The extension of the HEX surface is realized by lamella or fins.

Some examples of external heat exchangers are shown in Figure 2-4. These examples show that an external HEX can be part of a unit operation or the unit operation itself. Based on the specific application, the heat exchanger is used to heat a product or process medium.

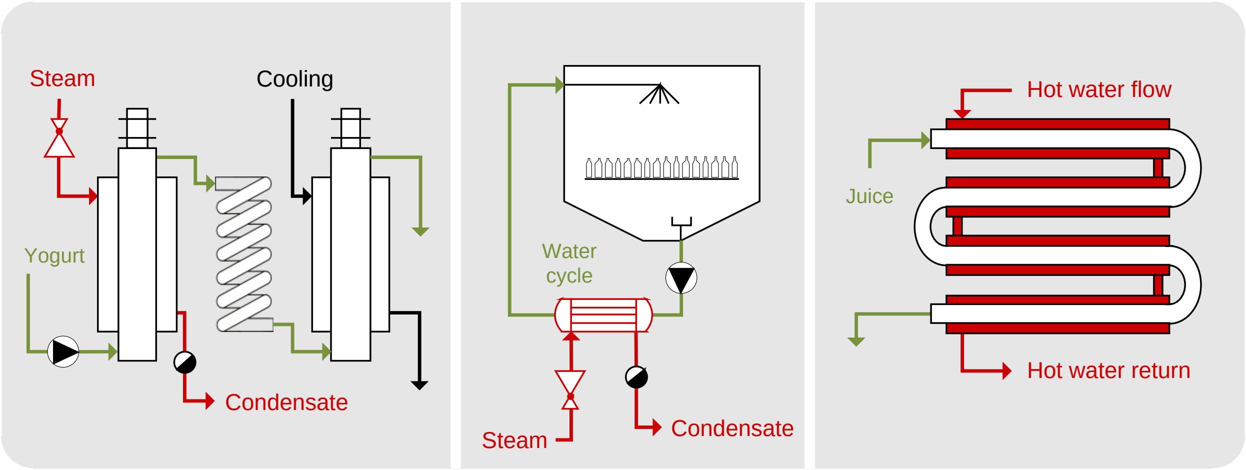


Figure 2-4: Examples of processes that are heated by external heat exchangers. Left: Pasteurization of yogurt with steam heated scraped surface heat exchangers. Centre: Tunnel pasteurizer heated by external tube bundle. Right: Pasteurization of fruit juice via double pipe HEX (Schmitt, 2014).

Besides external heat exchangers, machines, tanks, or baths can be supplied with thermal energy by **internal heat exchangers**. The most important types of internal HEX are heating jackets, heating coils, and tube bundles. Also plate coil HEX and electric heating elements are used. An example of some of these internal HEX types is shown in Figure 2-5.

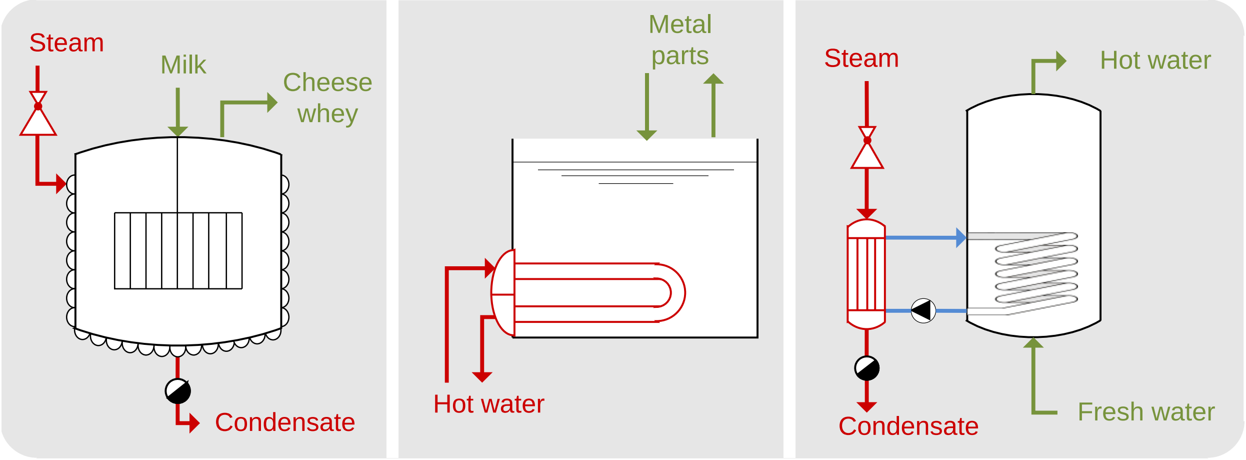


Figure 2-5: Process heating via internal heat exchangers. Left: Cheese production – a vessel with heating jacket is heated via steam. Centre: Heating of degreasing bath via internal tube bundle without shell. Right: hot water supply with internal heating coil that is heated indirectly via steam by an intermediate hot water circuit (Schmitt, 2014).

Heating jackets can be found in different variations such as full jackets, welded half pipes or profiles and so called dimple jackets. The utilization of full jackets is limited to a pressure of the heat transfer medium up to 6 bar and vessel sizes up to 10 m³. For larger volumes or higher pressures, welded coils, profiles, or half pipes are used (Sinnott et al., 2005; Vauck und Müller, 1988).

Heating coils are the most simple and cheapest heat exchanger types. A tube is helically wound around a cylinder and fitted with ports for inlet and outlet of the heating medium. Although the capacity of heating coils can be affected by pitch and diameter of the tube, the specific heat transfer rate is rather low due to the low flow rate on the outside of the tube (VDI GVC, 2006).

Although so-called panel- or plate coils are classified as compact heat exchangers by Shah et al. (2003), their main field of application corresponds rather to internal heat exchangers. Their construction equals roll bond absorbers. They are often used as an internal heating element or heating jacket to heat vessels or baths. Based on the material used, operating pressures of 7 to 18 bar are possible. Due to the simple production process, this heat exchanger type is very cheap (Shah et al., 2003).

In principle, electric heating elements are able to provide very high temperatures. However, they are also used to provide lower temperature ranges because of procedural reasons. So-called rod-type or pipe heating elements can be placed in fluids to heat them (Vauck und Müller, 1988; Wagner, 2005).

2.4.2 Direct heating systems

There are two important types of direct heating systems: direct combustion and steam injection. Using direct combustion systems, the firing flame room and flue gas pipes of an oil or gas burner are directly disposed in the facility to be heated (e.g. water bath for cleaning) and transfer the heat to the product or process medium.

Direct steam injection can be used to heat baths, tanks, and fluid streams or to provide an air-steam atmosphere. The direct heating of baths or vessels via steam can be realized by steam injection at the bottom of the vessel/bath using perforated tubes and coils or nozzles. By using nozzles, the product or process medium within the vessel/bath is sucked in, mixed with steam, and returned into the vessel/bath. Based on the specific properties of the heated product or process medium, the injected steam has to meet high standards (Vauck et al., 1988). Two examples are shown in Figure 2-6.

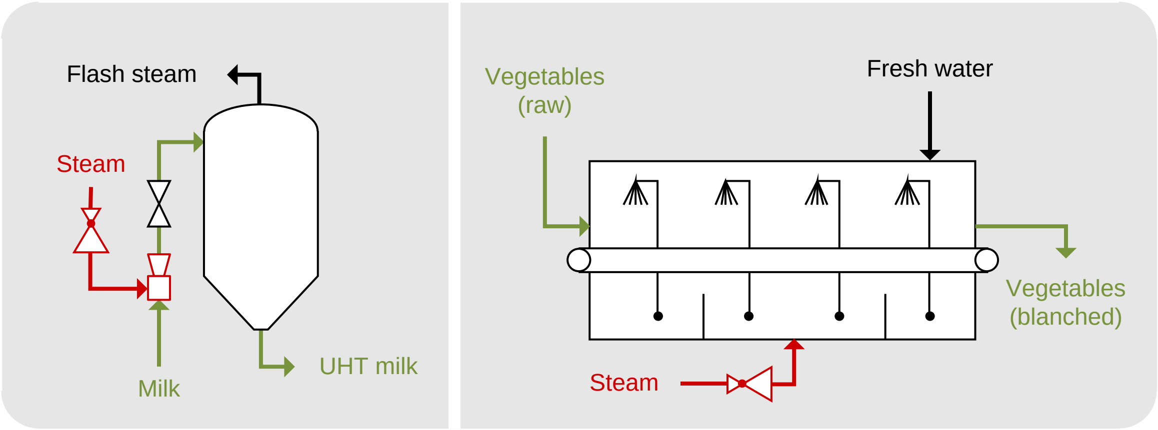


Figure 2-6: Process heating with direct steam injection. Left: Ultra high temperature sterilization of milk via direct steam injection and flash evaporation. Right: Belt blancher for vegetables heated by direct steam injection (Schmitt, 2014).

2.4.3 Evaporators and dryers

Evaporators and dryers can be equipped with internal or external heat exchangers and can be categorized within their own group. Since they are often heated using special heating mechanisms, they can be considered separate and not based on the placement of heat exchanger. Again, here is only some basic information necessary for the classification used in Chapter 5. For more details refer to the specific literature on this subject, such as Mujumdar A.S., 2006.

Evaporator types can be classified according to the evaporation mechanism. Important evaporator types are kettle reboilers, natural and forced circulation evaporators, and climbing and falling-film evaporators. Mainly, continuous steam heated evaporators are used, which are often designed as multiple effect evaporation systems (Goedecke, 2006).

For drying, a multitude of different dryer types are used within industry that can differ significantly in construction and mode of operation. Dryers are classified into convective-, contact-, radiation-, dielectric-, and freeze dryers. Out of these types, convective- and contact dryers can be supplied with solar thermal energy. Convective dryers mostly use air that is heated to dry products. Contact dryers use heated surfaces that are in direct contact with the product. These surfaces such as cylinders, plates or screws, are mainly heated by steam.

2.4.4 Heat pump concepts in industry

Heat pumps are an interesting concept for heat supply in industry, as they can supply heat to industrial processes (based on available waste heat), supply cold to processes and can be integrated with solar thermal systems (refer to IEA SHC Task 44, http://task44.iea-shc.org/). As heat pump concepts in industry might be specifically realized for certain unit operations, an overview of different heat pump types is given below.

Heat pumps are devices that are able to bring heat streams from a “heat source” to the “heat sink” at a higher temperature level through the input of high quality energy. They are designed to move energy opposite the direction of spontaneous heat flow from a cold space to a warmer one.

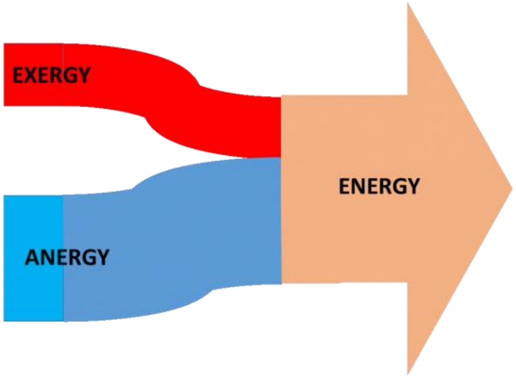


Figure 2-7: Transformation of anergy to useful energy via heat pumps

Thermodynamically speaking, they take the anergy (“non-useful” energy that cannot be transferred to usefule work) from the “heat source” and the exergy from a compressor to generate a heat stream at a useful temperature level at the heat sink. In general, heat pumps use a medium in a closed cycle that undergoes a phase change at two different pressures. The evaporation takes place at a low pressure and low temperatures. Through the compression of the evaporated fluid, the condensation temperature is raised and the condensation of the fluid will take place at a higher temperature. Different heat pumps use different technologies for the compression.

The maximum performance of such a heat pump is given by the “Carnot Law” and the temperature levels. The efficiency is expressed by the Coefficient of Performance COP. The theoretical limit is the Carnot COP:

$$COP_C = \frac{T}{\Delta T}$$

with T [K] as the heat sink temperature and ΔT [K] the temperature difference between heat sink and heat source. Practical heat pumps reach about 50 – 60 % of the theoretical value.

2.4.4.1 Vapor compression heat pumps

In vapor compression heat pumps a mechanical compressor performs the compression. The drive for the compressor is in general an electrical motor, but might be a combustion engine or a steam turbine as well.

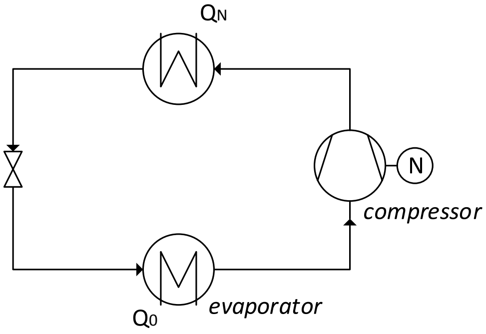


Figure 2-8: Closed cycle vapor compression heat pump

The amount of the useful heat is equal to the system’s COP and the amount of electrical energy consumed by the compressor: $Q_N = N \cdot COP$.

2.4.4.2 Absorption heat pumps

In absorption heat pumps, the compression of the fluid occurs differently. The evaporated working fluid is absorbed by a liquid (called “lean solution”), releasing the heat of absorption (about equal to the heat of condensation). The resulting “strong solution” is pumped to a higher pressure into the generator. Here the working fluid is desorbed by high temperature heat, producing the vapor that goes to the condenser on one hand, and the “lean solution” that goes back to the evaporator on the other hand. The driving power no is no longer a mechanical device, but the heat supplied to the generator. The power consumption of the pumps is comparatively small. The absorption heat pumps therefor have four heat flows: one into the system at the low temperature of the heat source, one into at the high temperature of the generator, and two heat flows out from the absorber and the condenser at the temperature level of the heat sink.

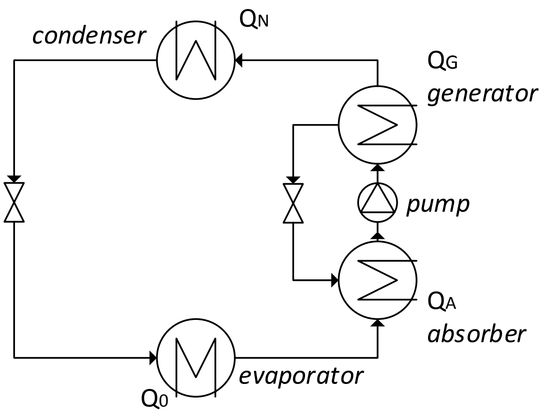


Figure 2-9: Closed cycle absorption heat pump

2.4.4.3 Open cycle heat pumps

In some industrial applications, a process medium can be used as the working fluid. A good example is the evaporation process where the vapor from the evaporator is used as a working fluid. The vapor is compressed in order to increase the condensation temperature and then can be used as a heating medium in the same process.

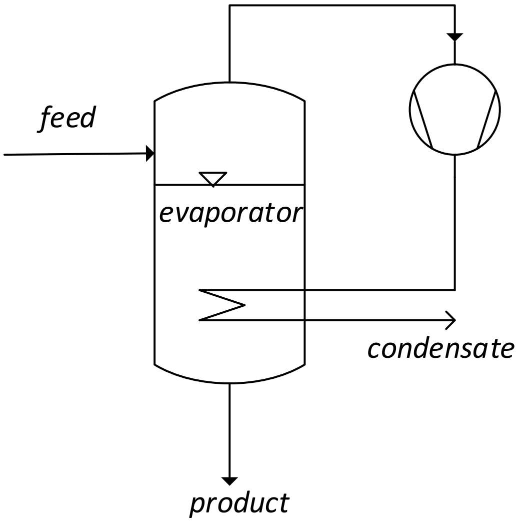


Figure 2-10: Vapor recompression heat pump (open cycle compression heat pump)

2.4.4.4 Heat pump working as dehumidifier

There is another possibility to use heat pumps in drying processes, by being mounted and used as a dehumidifier.

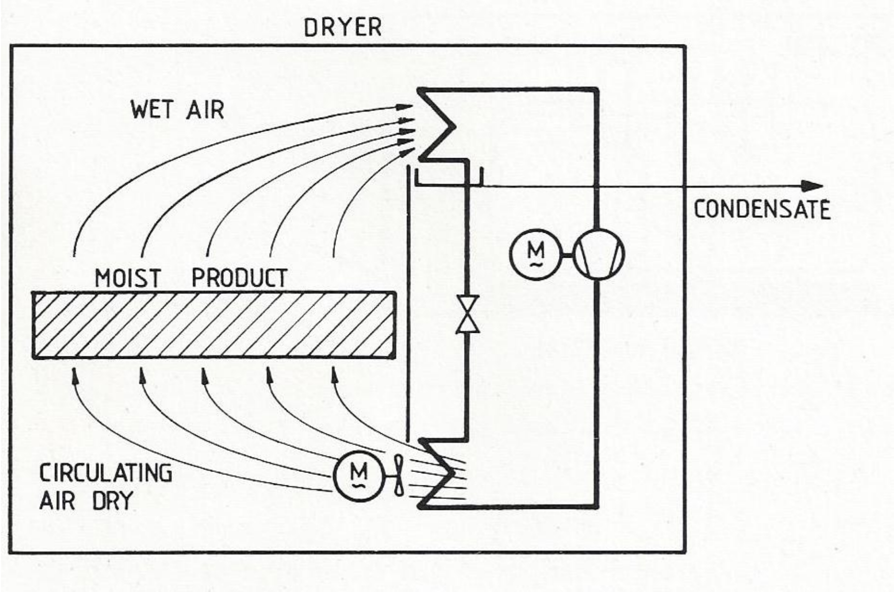


Figure 2-11: Heat pump working as dehumidifier (Source: Moser F., Schnitzer H.: Heat pumps in industry. Elsevier, 1985)

In this case, the drying medium (air in general) is cooled down in the evaporator of the heat pump below the dew point. The medium will release the humidity as liquid condensate, which is taken out of the dryer. The now dry air is reheated in the condenser and blown back to the dryer. Since the temperature difference between evaporator and condenser can be very small, the COP of such a system will be quite high.

2.4.5 Thermal storages in industry

To store thermal energy for processing requirements, hot water storages are by far the dominating technology. These hot water storages may be suitable for the integration of solar heat. Different configurations of these storages exist.

On the one hand, there are storages with a variable or fixed volume that are charged and discharged with hot water. In these open storages, charging does not occur only using thermal energy, but also with hot water as a medium to be filled or withdrawn. In most of these storages, the storage level varies according to the filling and emptying behavior. They are usually equipped with sensors for minimum storage level and an overflow. Since the charging and discharging of theses storages can happen in a relatively short time with high flow rates these storages might not be stratified compared to dedicated solar heat buffer stores.

On the other hand, there are closed buffer storages that are energetically charged and discharged. Usually these storages are heated using internal or external heat exchangers. Such storages can be connected to several processes or energy supply units for charging and discharging. They are usually better stratified than open storages, and in principle, solar heat can be well integrated next to the existing charging and discharging ports.

A multitude of both storage types (open and closed storages) can be connected in series or parallel to cover the demand of the company.

Another common storage type within industry is the hot water cascade. This type is used to provide hot water through the direct utilization of steam. A hot water cascade is usually a vertical store that is fed with the hot water return in the upper part. The return trickles over perforated plates and is heated by the steam in counter flow. In the lower part of the cascade, the hot water flow is withdrawn.

2.5 Cold Supply of Processes

Cooling is decisive in many industrial processes. In the chemical and steel industries, cold is required to cool products and equipment of exothermal processes, while in the food industry refrigeration is required to ensure food quality. Table 2-2 lists examples of industrial processes with selected parameters and cold demand.

In industry, cold is supplied to the processes either directly, in the case of the refrigerant that is transported and evaporates at the process, or through an intermediate cooling medium, such as glycol-water mixture, that is cooled in the evaporator and delivers cold to the processes using a heat exchanger. Both systems have their merits and drawbacks: while direct cooling reduces the losses of heat exchange, the transport of the refrigerant requires sensible operation, as small variations in refrigerant temperature affect the efficiency of cooling plants substantially. Basically, the equipment for cold supply, evaporators or heat exchangers, is in analogy to the equipment used for heat supply.

The most common type of cooling machines in industry is the electrically driven compression chiller. For solar to supply process cold, another type of chiller mainly referred to as an absorption chiller, is most relevant. In absorption chillers, the electrical compressor is replaced by a thermal compressor: the refrigerant is absorbed by a liquid solvent and pumped to higher pressure with only minimal power input, since the fluid is incompressible. At a high pressure level, the refrigerant is desorbed from the solvent, which requires thermal energy for the endothermic desorption process. Energy demand is thus shifted from electricity demand to heat demand. An important complementary component to absorption cooling machines is the heat rejection system for the absorber and the condenser. Based on its thermodynamics, the heat to be rejected in absorption cooling is much higher in comparison to mechanical compression chillers and the efficiency of cooling machines are significantly influenced by the efficiency of their heat rejection system. For further details refer to specific literature (e.g., Kohlenbach et al., 2013).

For industrial cold supply absorption, cooling is most economical when waste heat is available so that the heat generation does not incur costs. For plant retrofitting, the design of heat rejection systems is a challenge as the existing rejection systems from the compression chillers will usually not be sufficient. These challenges (low cost heat and low cost heat rejection) already indicate that in countries with moderate climate solar supplied absorption cooling faces an economic challenge. One promising way for absorption cooling is to integrate the heat demand for cooling into the thermal heat system of the company. In that way, waste heat, solar heat and possibly heat from cogeneration plants can act synergistically to supply the thermal system (e.g., heat loops or storages) and different processes, absorption cooling being one of them.

An important aspect for the supply of industrial cold demand with absorption cooling is the availability of such systems on the market. Currently, there is a lack of machines on the market for the medium power range (from 50 to 500 kW).

In this guideline, the heat required by an absorption heat pump for cooling is seen as a heat sink (comparable to any other process with heat demand) so the concepts presented in the next chapters can be adopted. Dedicated material on solar cooling is available from other IEA SHC Tasks. A comprehensive textbook was recently published (Henning et al., 2013).

Table 2-2: List of selected cooling processes in industry (AEE INTEC, 2012)

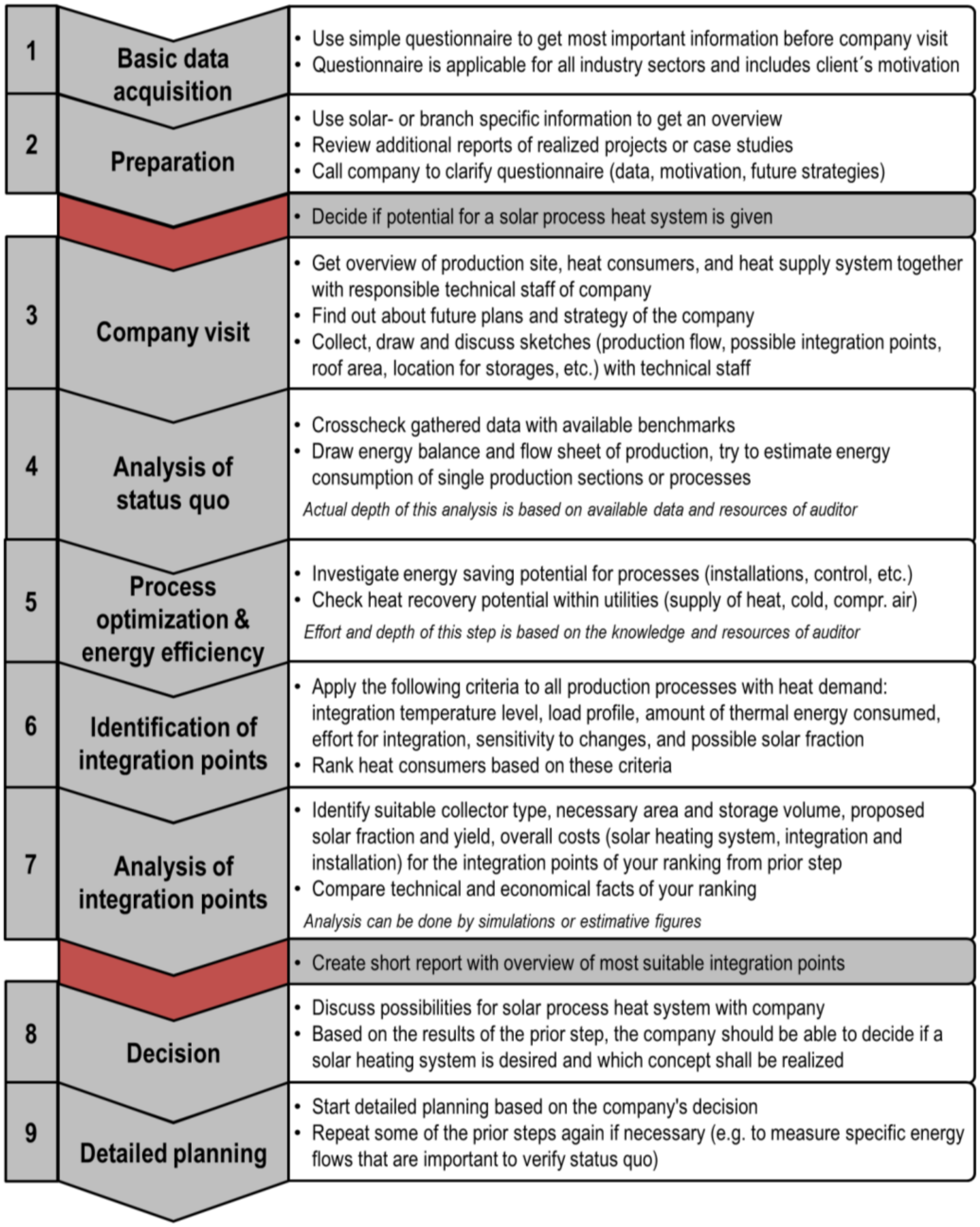
Unit operation	Load profile			
	Typical demand range and variability		Temperature profile and typical cooling system	
Brewery				
fermentation	1 MW	batch with variable load; continuous via parallel processing	4 - 13°C	direct evaporation or indirect cooling
yeast tanks	30 kW	batch with variable load	6°C	indirect cooling
storage cooling	1 MW	continuous with variable load	0/-1°C	direct evaporation or indirect cooling
Dairy				
milk pasteurization	100 kW	continuous	6°C	
product cooling (whey)	500 kW	continuous	45 - 8°C	river cooling or indirect cooling; partly heat recovery
product cooling (whey concentrate)	100 kW	continuous	50 - 20°C	river cooling or indirect cooling; partly heat recovery
product cooling (cream)	200 kW	continuous	50 - 8°C	river cooling or indirect cooling
product cooling (milk for cream)	10 kW	batch	8 - 10°C	indirect cooling
product cooling (cream)	100 kW	batch	21°C - 11°C	indirect cooling
equipment cooling (butter)	50 kW	batch	2 - 11°C	indirect cooling
product cooling (butter milk)	10 kW	batch	6°C	indirect cooling
product storage		continuous	4 - 6°C	indirect cooling
Meat processing				
air conditioning in production	100 – 150 kW	continuous with variable load	+12 - 14°C	direct evaporation or indirect cooling
cold storage	300 – 500 kW	continuous with variable load	+1 - 4°C	direct evaporation or indirect cooling
storage (freezing)	80 – 150 kW	continuous with variable load	-25°C	direct evaporation or indirect cooling
storage (shock freezing)	50 kW	continuous with variable load or batch	-30°C	direct evaporation or indirect cooling
Bakery				
storage	10 kW	continuous	+2°C 8°C	direct evaporation or indirect cooling
fermentation	150 kW	batch	-7°C	direct evaporation or indirect cooling

shock freezing	200 - 300 kW	batch with variable load; continuous via parallel processing	-30°C	direct evaporation or indirect cooling
storage (freezing)	40 - 60 kW	continuous with variable load	-25°C	direct evaporation or indirect cooling
Fruit & vegetable trading				
storage	200 - 500 kW	continuous with variable load	+2°C - 4°C	direct evaporation or indirect cooling
Food trading				
storage (fruits & vegetables)	40 – 60 kW	continuous with var. load	+6 - +14°C	direct evaporation or indirect cooling
storage	150 - 350 kW	continuous with var. load	+1 - 6°C	direct evaporation or indirect cooling
storage (freezing)	20 - 40 kW	continuous with var. load	-25°C	direct evaporation or indirect cooling
air conditioning in production	50 kW	continuous with var. load	20°C	direct evaporation or indirect cooling
Server farms				
air conditioning of server rooms	1 - 5 MW	continuous	20°C	river cooling or indirect cooling
Paint shops				
process cooling (cathodic painting)	50 - 200 kW	continuous	30°C	indirect cooling
process cooling (paint dryer)	30 – 100 kW	continuous	25°C	indirect cooling
intermediate product cooling	500 - 1200 kW	continuous	25°C (10 - 14°C glycol)	indirect cooling
equipment cooling (welding machines)	150 kW	continuous	40°C	indirect cooling
air conditioning in production	20 - 105 kW		3 - 20 °C	
Production of tools				
equipment cooling (machines)	5 – 100 kW	continuous	20 - 30°C	river cooling or indirect cooling
Process cooling in paper mills and steel production				
cooling of products	200 – 500 kW	continuous	20°C	river cooling or indirect cooling
agriculture				
storage cooling	20 – 50 kW		-3 - 15°C (about 80 % ca. 4°C)	
Processing of plastics				
equipment cooling (injection molding)			5 - 15°C	

3 Assessment Methodology for Solar Heat Integration

Bastian Schmitt

The effort for identification of suitable integration points for solar heat as well as the number and complexity of possible integration points can vary significantly between industrial sectors and individual factories. To assist with the necessary steps for a feasibility assessment, the methodology illustrated in Figure 3-1 can be used. This methodology can be divided into three main parts: pre-feasibility assessment (steps 1 and 2), feasibility study (steps 3 to 7) and decision/further activities (steps 8 and 9). In the following, the single steps are briefly described.



1	Basic data acquisition	• Use simple questionnaire to get most important information before company visit • Questionnaire is applicable for all industry sectors and includes client´s motivation
2	Preparation	• Use solar- or branch specific information to get an overview • Review additional reports of realized projects or case studies • Call company to clarify questionnaire (data, motivation, future strategies)
		• Decide if potential for a solar process heat system is given
3	Company visit	• Get overview of production site, heat consumers, and heat supply system together with responsible technical staff of company • Find out about future plans and strategy of the company • Collect, draw and discuss sketches (production flow, possible integration points, roof area, location for storages, etc.) with technical staff
4	Analysis of status quo	• Crosscheck gathered data with available benchmarks • Draw energy balance and flow sheet of production, try to estimate energy consumption of single production sections or processes *Actual depth of this analysis is based on available data and resources of auditor*
5	Process optimization & energy efficiency	• Investigate energy saving potential for processes (installations, control, etc.) • Check heat recovery potential within utilities (supply of heat, cold, compr. air) *Effort and depth of this step is based on the knowledge and resources of auditor*
6	Identification of integration points	• Apply the following criteria to all production processes with heat demand: integration temperature level, load profile, amount of thermal energy consumed, effort for integration, sensitivity to changes, and possible solar fraction • Rank heat consumers based on these criteria
7	Analysis of integration points	• Identify suitable collector type, necessary area and storage volume, proposed solar fraction and yield, overall costs (solar heating system, integration and installation) for the integration points of your ranking from prior step • Compare technical and economical facts of your ranking *Analysis can be done by simulations or estimative figures*
		• Create short report with overview of most suitable integration points
8	Decision	• Discuss possibilities for solar process heat system with company • Based on the results of the prior step, the company should be able to decide if a solar heating system is desired and which concept shall be realized
9	Detailed planning	• Start detailed planning based on the company's decision • Repeat some of the prior steps again if necessary (e.g. to measure specific energy flows that are important to verify status quo)

Figure 3-1: Assessment methodology for solar heat integration

The purpose of the pre-feasibility assessment is to quickly find out if solar heat can be used in a company. Therefore, basic information should be gathered after the initial contact. This can be done by phone or by a questionnaire that is sent to the company. The most important information is the temperature level of consumed process heat, the available roof- or ground areas for solar heating systems, the production times, and the investment policy of the company. In addition, branch specific information and reports on realized projects or case studies could help to assess the general possibilities for integrating solar heat within a specific sector. Based on this information, a decision can be made to or not to use solar heat.

If the potential for a solar process heat system is given, a feasibility study can be carried out. It starts with a company visit to get an overview of the production site, heat consumers, and heat supply system as well as to find out about future plans and the strategy of the company. At this time, it is helpful to collect, draw, and discuss sketches (production flow, possible integration points, roof area, location for storages, etc.) with the technical staff of the company. Based on the information gathered and relevant data provided by the company, the status quo is then analyzed by crosschecking the gathered data with the available benchmarks, drawing energy balances and flowsheets of production processes, and trying to estimate the energy consumption of single production sections or processes. The actual depth of this analysis is based on available data and resources of the auditor.

The next step is to estimate the potential for heat recovery and energy efficiency measures. Similar to step 4, the effort and depth of this step is influenced by the knowledge and resources of the auditor. At minimum, common heat recovery measures within utilities (supply of heat, cold, and compressed air) should be considered. The advantage of a detailed process integration study is that besides the identification of heat recovery options, the study helps to identify which processes at which temperature levels are the sensible options for solar heat integration. Based on the energy consumption of different production sections or processes and the consideration of energy savings, integration points for solar process heat can be identified (step 6). For these pre-selected integration points, the following criteria can be applied to all production processes with thermal energy consumption:

- Integration temperature level
- Load profile (daily, weekly, annually)
- Amount of thermal energy consumed annually effort for integration
- Sensitivity to changes
- Achievable solar fraction

Based on these criteria, the heat consumers can be ranked. Based on this ranking, the best integration points are analyzed in more detail within step 7 (see Chapter 7). A suitable collector type must then be identified for each integration point and along with the necessary area and storage volume. In addition, the proposed solar fraction, yield, and overall costs must be estimated. The costs should cover the solar heating system, integration, and installation. This analysis can be done using simulations or estimated figures. Considering the technical and economic facts of the considered integration points, the ranking of step 6 may be rearranged.

Based on the results of the feasibility study, the different possibilities for integrating solar process heat should be discussed with the company. With information on the level of effort for implementation, estimated costs, and expected savings, the company should be able to decide if a solar heating system is desired and the concept to be used. Detailed planning is then carried out based on this decision. It may be necessary to repeat some of the steps (e.g., to measure specific energy flows that are needed to verify status quo).

The scope of this document only includes steps 1-6. Details on solar thermal system design will be given elsewhere (upcoming IEA SHC Task 49 Handbook).

4 Process Integration for Solar Process Heat Projects

Pierre Krummenacher, Bettina Muster

Highlights:

- Holistic view on energy efficiency and solar heat may enable more efficient and more economic SHIP installations
- Methodological approaches for analyzing waste heat recovery and identification of integration points for new heat supply exist
- Pinch analysis is a powerful tool for identifying promising integration points, on supply and process level
- Combined simulation on heat recovery and solar heat are important for detailed analysis

The aim of this chapter is to highlight the importance of a holistic view on energy efficiency, heat recovery and renewable heat supply which holds true especially for designing solar process heat projects. Process integration studies allow for this combined approach and provide a valuable basis for solar process heat design.

After demonstrating the potential of heat recovery in industry, this chapter introduces Pinch Analysis as one process integration methodology. Different ways on how solar process heat can be designed based on the result of the Pinch Analysis are shown and discussed. Finally, a “workflow” for realizing a solar process heat project based on process integration summarizes the combined approach.

4.1 The importance of thermal energy efficiency and process integration in industry

The ambitious goals for reducing fossil energy consumption in industry will only be met by a holistic approach of energy efficiency measures combined with renewable energy resources. According to the “Roadmap for moving to a competitive low carbon economy in 2050” (EU, 2011), the European Union targets a reduction of approximately 80 % of greenhouse gas emissions until 2050 (compared to 1990). By analyzing the implementation of the energy efficiency potential in industry (e.g., see energy efficiency index ODEX of the EU-27(European Environment Agency, 2011)), it becomes clear that it will be vital to focus on energy efficiency solutions in each industrial energy audit to maintain a competitive European manufacturing industry.

It is important to highlight that the large saving potential of “energy efficient processes” can only be tapped by a universal vision, combining technological improvements with intelligent integration of available waste heat and renewable energies. For the integration of solar thermal heat in industry, it is especially important to consider heat recovery. The quantity and temperature of freely available waste heat will influence the planning and design of a solar thermal system – from a thermodynamic as well as a an economical point of view – and companies will aim to synergistically integrate waste heat as a free energy source with other additional energy supply technologies, such as solar process heat.

The consideration of ideally suited load profiles and temperature levels for solar thermal integration has led to a sustainable design of solar thermal systems. The detailed consideration of available waste heat and necessary energy demand on different temperature levels can help the solar planner to design an efficient industrial process combining heat integration with a solar thermal heat supply and to ensure that solar heat will go beyond the heat recovery potential.

Industrial waste heat is poorly quantified, but various studies have estimated that as much as 20% to over 50% of industrial energy consumption is ultimately discharged as waste heat[2], (IES IETS Draft Annex, 2010 and Berthou, 2012). While some waste heat losses are inevitable, a large proportion of the above amount can be saved by resorting to various techniques, such as:

- thermal insulation (reported to be 5% of the industrial energy consumption),
- direct heat recovery via heat exchangers to preheat process streams,
- heat recovery and upgrading to appropriate temperature level by means of heat pumps, thermal vapor recompression, etc.,
- heat recovery from high temperature heat sources (e.g., flue gas) to generate electricity,
- considering low temperature heat sources for organic Rankine cycle electricity generation, and
- technological changes.

Within the European project EINSTEIN (EINSTEIN, 2012), 72 thermal energy audits have been performed throughout Europe. These studies show that the energy saving potential in industry is in the range of 10 to 30 %. These are average figures, showing large variations depending on industrial sectors, types of processes, framework conditions, etc. However, they prove that a large potential for energy efficiency exists. The largest savings can be identified with a holistic approach on energy optimization and renewable energy integration.

Available energy efficiency tools and manuals

To achieve energy efficiency solutions in industry, tools and manuals are necessary to promote possible solutions and to build awareness among companies and suppliers. As some energy efficiency solutions are sector specific, there are a number of tools and manuals available giving general applicable energy efficiency measures, optimization approaches and/or sector-specific solutions. The following is an initial list of information sources:

- Best Available Techniques (BAT) reference documents (BREFs) from the European Integrated Pollution Prevention and Control IPPC Bureau: http://eippcb.jrc.ec.europa.eu/reference/
- EINSTEIN Experts System for an Intelligent Supply of Thermal Energy in Industry and other Large-Scale Applications: http://www.einstein-energy.net
- BESS benchmarking tool for energy efficiency in Small and Medium Sized Enterprises: http://www.bess-project.info/

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[2] IES IETS Draft Annex, 2010 / Waste Heat Recovery – US DoE /

- Guidance Note on Energy Efficiency Auditing: http://www.epa.ie/pubs/advice/licensee/guidancenoteonenergyefficiencyauditing.html
- Cleaner Production – Energy Efficiency Manual: www.uneptie.org
- Energy efficient technologies and measure for increasing efficiency – proven applications and innovations: http://www.umweltbundesamt.at/fileadmin/site/publikationen/M172.pdf
- United Nations Environment Programme: http://www.unep.org/energy/
- Optimal Audit: http://www.cheme.utm.my/prospect/index.php/software/19?task=blogcategory.

More information can be found in the information data pool of the project Greenfoods: http://wiki.zero-emissions.at/index.php?title=Greenfoods_tools .

4.2 Process Integration – as a Basis for Solar Thermal Integration

The basics of the general methodology for the integration of solar thermal energy into industrial processes introduced in Chapter 3 was initially developed during the IEA SHC TASK 33/IV. This work showed that process integration for the total production site is one of the best approaches for an intelligent integration of solar thermal energy. Process integration analyzes the production system with a holistic view of all processes and supply equipment, gives insights into energy demand over time on different temperature levels, and shows optimization potential via technology improvement, efficiency enhancement and heat recovery. Obviously, the degree of detail and depth of an energy efficiency analysis/process integration study during a study on solar heat for industrial processes will depend primarily on the resources and know-how of the energy planner. Detailed process integration studies are recommended as they can serve as an ideal basis for an optimized integration concept for solar process heat.

Owing to its systemic and optimization approaches, process integration (using Pinch Analysis and/or other advanced methods) features major advantages as it brings:

- Insight in the system and its specific bottlenecks,
- Solutions for energy and/or material efficiency,
- Help to plan process modifications,
- Optimized design of a profitable energy mix for renewable energy supply in conjunction with heat recovery.

The combination of energy efficiency analysis and solar heat integration usually leads to higher energy and respective CO_2 savings and to higher profitability of the solar process heat project. Nevertheless, experience shows that a process integration study of an existing site can be difficult to sell to the industry in addition/combination to a solar process heat project, for several reasons, including notably:

- A time consuming data collection required by this global approach prior to achievement of any outcome/saving potential (although these data are needed for appropriate solar thermal system design),
- Financial and/or human resource limitations (and priority is given to solar heat if this project is of strategic importance for the industry).

To allow for selling a process integration study against the potential obstacles mentioned above, it can roughly be distinguished between different levels of detail of the process integration study depending on the chosen level for integration of solar heat: An integration at supply level requires generally a lower degree of detail compared to a process level integration.

In the methodology for the integration of solar thermal energy into industrial processes developed during the IEA SHC TASK 33/IV specifically the Pinch Analysis, a classical tool for process integration, was highlighted. However, it must be noted that there are other methods available as well. To introduce the reader to process and heat integration, we will first give a short overview on Pinch Analysis. Further, the use of this analysis for solar thermal integration will be shown. Available tools are shown in the Appendix 0.

4.2.1 Pinch Analysis

The Pinch Analysis is a classical methodology for analyzing heat recovery potential for an industrial process or a total industrial site (see e.g. Nemet A., Klemeš J.J., 2011) and to design utilities for energy supply. It can also be used to design the best heat recovery and utility mix based on a fixed utility system (e.g. envisioned solar heat supply). In Appendix 0 the methodology is exemplified by means of a simple process derived from VDI (2006).

Data collection & extraction: A Pinch Analysis begins by establishing a list of heating requirements (named cold streams, or heat sinks) as well as of cooling requirements (named hot streams or heat sources) of the whole production site (Figure 4-1). Streams that are not required for the process (such as waste water running to the effluent) can be included if they are used for cooling or as a heating medium for other streams. Each stream is defined by its mass flow, specific heat and inlet, and target temperature (or phase change enthalpy).

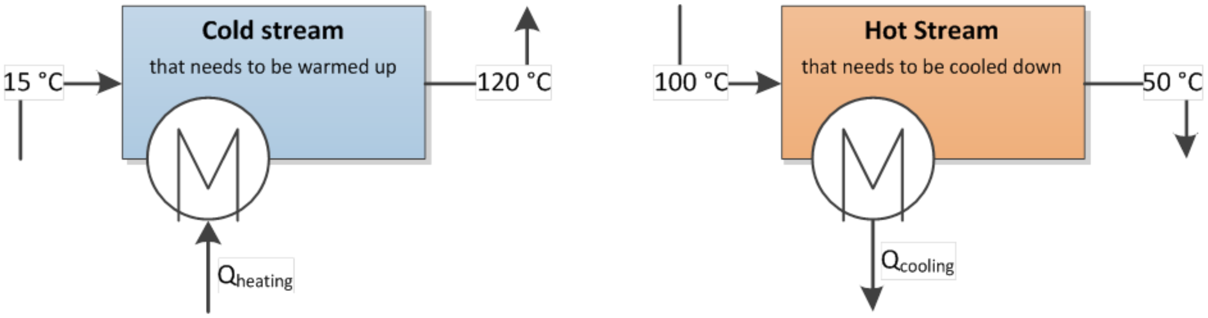


Figure 4-1: Cold and hot streams in the Pinch Analysis

Targeting: The Pinch Analysis offers two graphs showing the targets for

- Maximum heat recovery
- Most efficient energy supply

The first target can be visualized in the Composite Curves (CCs), the latter in the Grand Composite Curve (GCC).

Composite curves: To determine the heat recovery potential specific to the site, the individual temperature enthalpy profiles of cold streams are combined into one global profile (resulting in the so-called cold composite curve), and similarly for the hot streams (resulting in the hot composite curve).

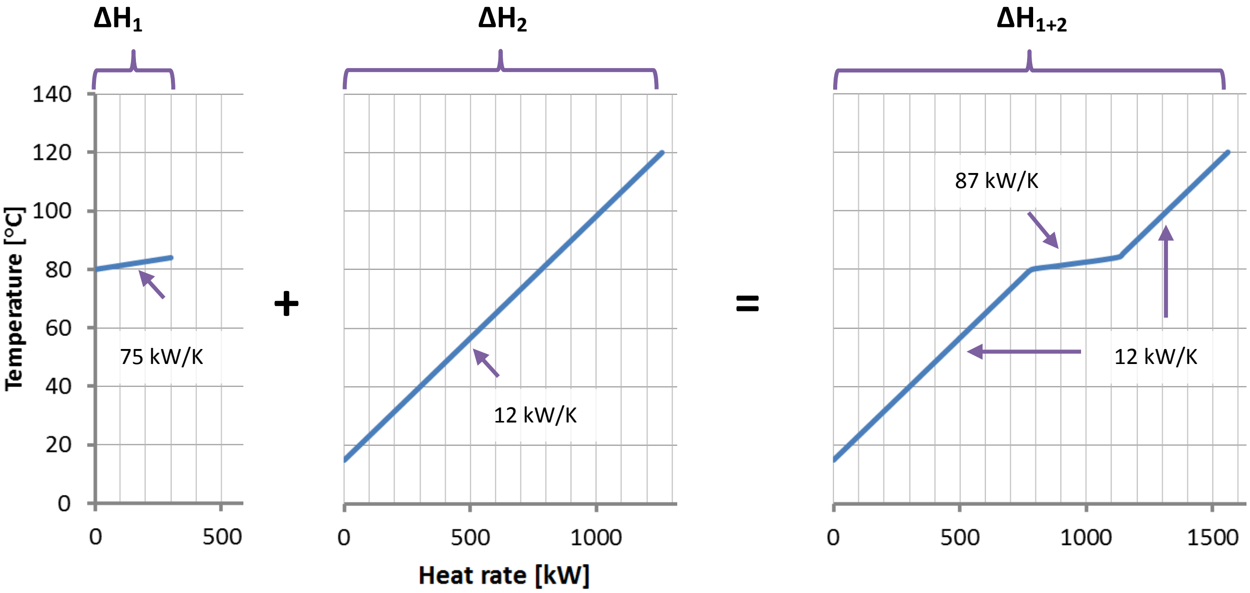


Figure 4-2: The cold composite curve – it is constructed by summing up the enthalpy changes of each stream in each temperature interval. In temperature intervals with several cold streams, the slope values are added.

Both curves are then drawn on the same temperature-heat duty diagram in such a way that the cold streams (i.e. cold composite) are at a lower temperature than the hot streams (i.e. hot composite) everywhere in the diagram (see Figure 4-3). This can be achieved by moving the curves along the energy axis, as an energy value always represents a relative and not an absolute measurement. This way the maximum possible energy transfer (heat recovery) becomes visible. With the help of these composite curves (CCs) it is possible to determine some essential facts about the process. The curves are separated by a point of the lowest (vertical) temperature difference ΔT_{min} that is chosen by the user as the minimal ΔT over a possible heat exchanger in the system (this global ΔT_{min} is an economic parameter representing the optimal trade-off between energy savings and capital costs). This ΔT_{min} defines the temperature level in the system that can be explained as the thermodynamic bottleneck of the process, the so-called "Pinch". The exact Pinch point lies in the middle between the HCC and the CCC, which is 77.5°C in Figure 4-3.

The horizontal overlap between the curves in Figure 4-3 shows the maximum possible heat recovery. The minimum heating demand (hot utility) $Q_{H, min}$, and the minimum cooling demand (cold utility) $Q_{C, min}$ can also be identified from the figure. The minimum temperature difference ΔT_{min} is determined by economical optimization, as a lower ΔT_{min} increases the efficiency of heat exchange, but also increases heat exchanger surfaces and costs. The composite curve identifies the beneficial process modifications (change of operation conditions: pressure, temperature, etc.) that may shift the heat sinks or heat sources to increase the heat recovery potential.

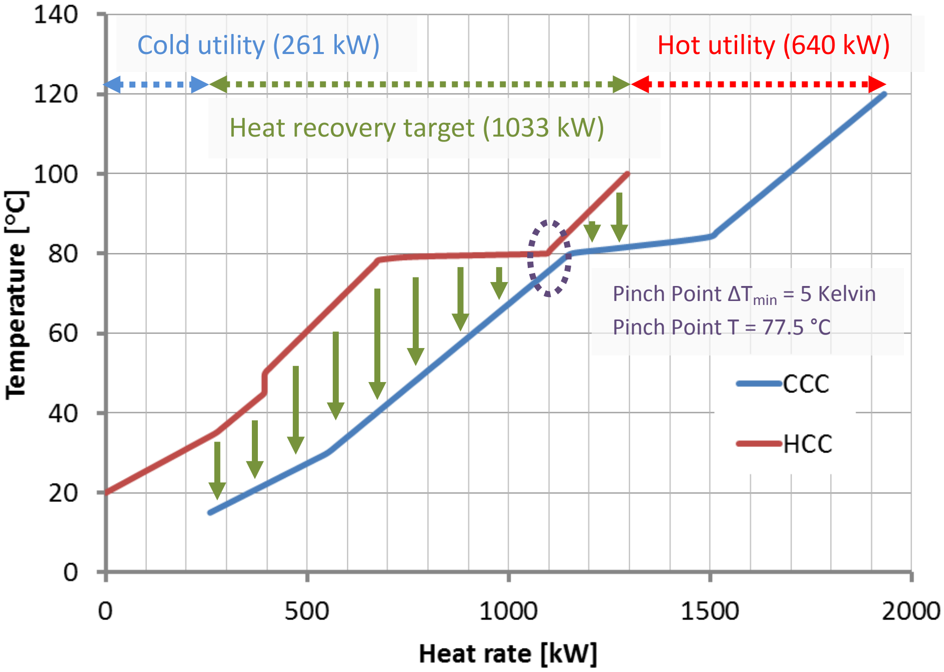


Figure 4-3: Hot and cold composite curves

The Pinch temperature cuts the system in two halves: in an area below the Pinch temperature (the part of composite curves on the left of Pinch) with a heat surplus that has to be removed by external cooling and an area above the Pinch temperature (the part of composite curves on the right of Pinch) with an energy deficit that has to be overcome by additional heating. Three important rules for heat integration follow:

- No external heating below the Pinch temperature (since there is enough waste heat available, an additional integration of heat sources below the Pinch will increase the cooling demand by cold utilities).
- No external cooling above the Pinch temperature (since cooling can be achieved by heating other cold process streams, otherwise unnecessary heating utility use is needed).
- Do not transfer heat from heat sources above to heat sinks below the Pinch

Of course, the targets values given by the CCs hold for the ideally heat integrated situation assuming heat from hot process streams can be transferred to cold process streams i.e. the process heat transfer is technically feasible at affordable costs (e.g. not hindered by heavy fouling properties, etc.). If some streams obviously not do fulfill these requirements, these streams should not be included in the composite curves and the Pinch temperature may change.

Further, the CCs provide no information about the lowest temperature level at which the hot utility is actually required (respectively the highest temperature level of cold utility). To address this issue, necessary for the appropriate selection and optimization of utilities and especially relevant for selection the solar heat integration, another curve is used, called **the *grand composite curve (GCC).*** The GCC represents then the temperature profile of the remaining heating (respectively the remaining cooling) requirements. The curve is directly derived from the hot and cold composite curves and its construction is demonstrated in Appendix A. The GCC, for example, is the essential basis for deciding whether a heat pump or a cogeneration unit is potentially attractive and, if they are, at which size. Similarly, for solar heat integration, the GCC provides the key information of the possible maximum heating rate contribution of the solar thermal system as a function of its operation temperatures. The GCC can also be drawn based on the existing utilities.

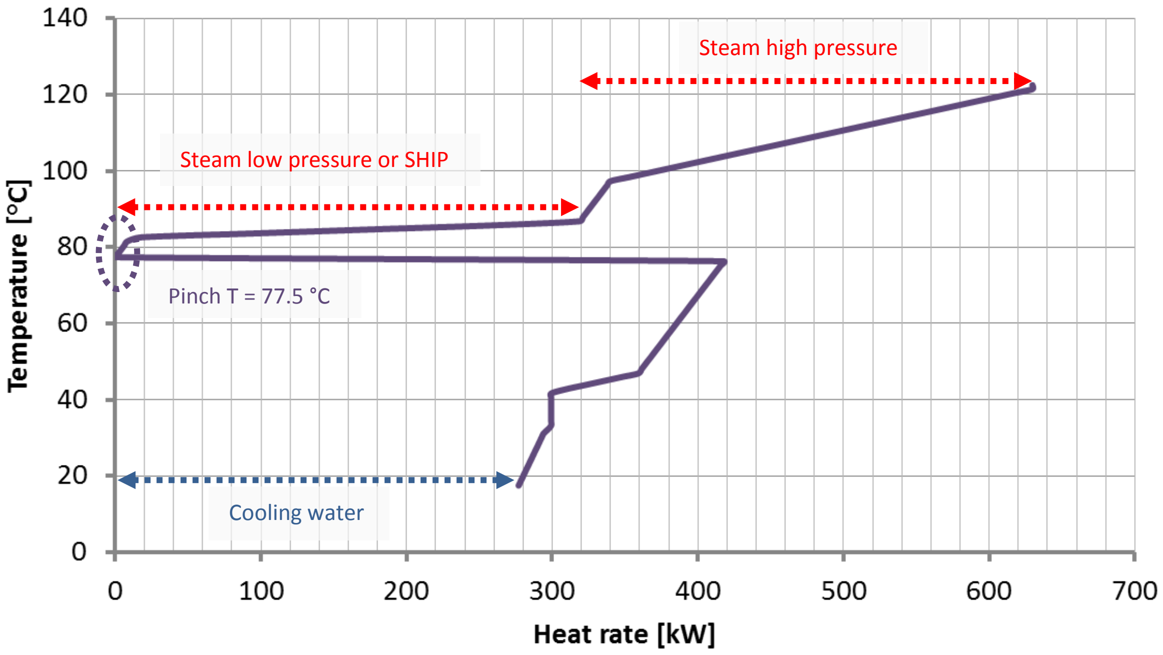


Figure 4-4: Grand composite curve

The GCC also allows evaluating the combined use of heat pumps and solar heat. According to the rules defined by the Pinch technology, heating below the Pinch and cooling above the Pinch is not allowed. For the correct placing of a heat pump this means that the evaporator (cold end) of the heat pump has to be placed below the Pinch and the condenser (hot end) above the Pinch. By doing so, there is a double effect: the heat pump reduces the cooling load and the heating load at the same time. Since both heat exchangers operate at constant temperatures (phase change of a single fluid), two horizontal lines will be added in the hot and cold composite curves, if the heat pump exchangers are treated like process equipment. The grand composite curve shows exactly the temperature levels and their power for heating or cooling. For solar heat integration there is the additional possibility to integrate low temperature solar heat together with waste heat as low temperature heat source for the heat pump.

Design: Once the utilities have been selected and sized (flows, operation temperatures) according to the GCC, one can integrate the utilities again in the composite curves. On this basis, the practical placement of the heat exchanger network can be identified. Here, automated optimization algorithms have been developed that suggest the most energy efficient and cost effective heat exchanger placement.

4.2.2 The use of Pinch Analysis for the Integration of solar heat into industrial processes

When it comes to integrating solar heat into thermal energy systems of a production site, the question of choosing the most suitable integration point, in terms of technical and economic aspects, has to be tackled. Solar heat can be integrated to a specific unit operation ("on process level") or into the utility system ("on supply level") as e.g. heating of make-up water of the steam system. The integration point is defined as the interface between the solar plant (including solar heat storage) and the heat sink side (materialized by a heat exchanger transferring solar heat to the heat sink, or a valve / pipe connection if the heat sink media flows through collector/solar buffer storage as well).

To address the integration of solar heat by the Pinch Analysis, there are two main challenges:

1) The time dependency of the solar heat availability needs to be reflected in the analysis and
2) The solar heat gains will not be known in detail until the solar process heat system concept and especially the integration return temperature and the maximum integration flow temperature are defined.

The Pinch Analysis based methodology aims at identifying the most promising options for solar integration, while ensuring that other cost effective alternatives aren't overlooked. Several possibilities to analyze solar heat integration based on the graphs are presented in the Appendix 0 based on a simple process example.

Most importantly we can summarize that the potential to integrate solar heat as a utility can be analyzed based on the GCC. Process changes and heat recovery implementation will change the GCC and show the effects for solar integration possibilities. This is visualized in the following figure for a packaging example (for details, the reader is referred to Appendix 0). The dotted lines represent several ways of theoretically integrating solar heat against the GCC to ensure adequate performances. In Figure 4-5 the GCC on the left includes several heat recovery options, whereas the GCC on the right does not take heat recovery into account. It becomes obvious that the potential for integrating solar heat changes significantly which highlights the importance of the combined analysis of heat integration and solar heat supply.

After evaluating the potential to integrate solar heat based on the GCC (including temperature levels), it has been determined that solar heat can also be added as a hot stream to the composite curves. Based on the composite curves, it is often more apparent to identify the practical integration point for the solar thermal system.

Integrating solar heat into the composite curves will also quickly reveal whether the heat recovery potential is affected by the solar heat integration. If solar heat is integrated at the correct temperature level, the potential for heat recovery will not be decreased and minimal cooling demand should not be increased.

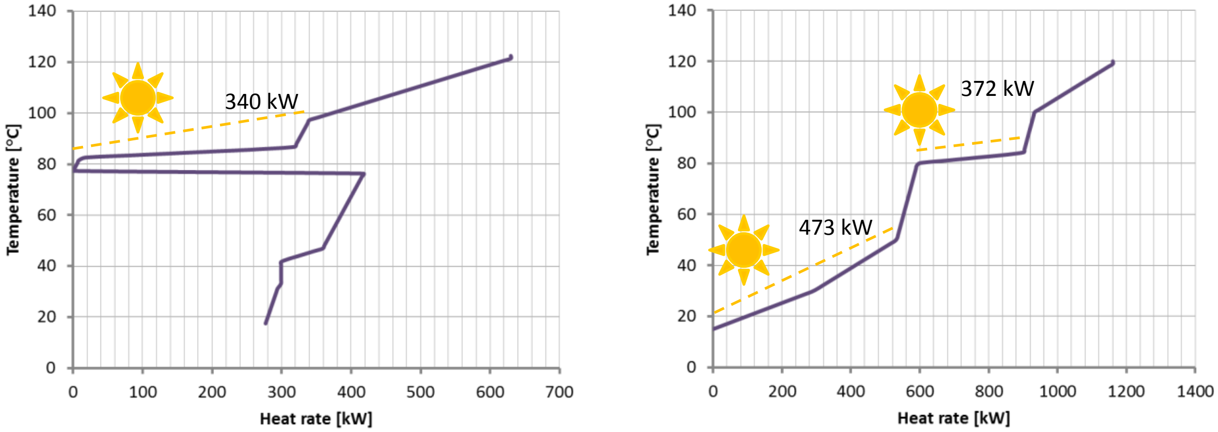


Figure 4-5: GCC of a food packaging line including heat recovery options (left), and GCC excluding most heat recovery options (right) at ΔT_{min}=5°C. Note that the scales of the x-axis are different.

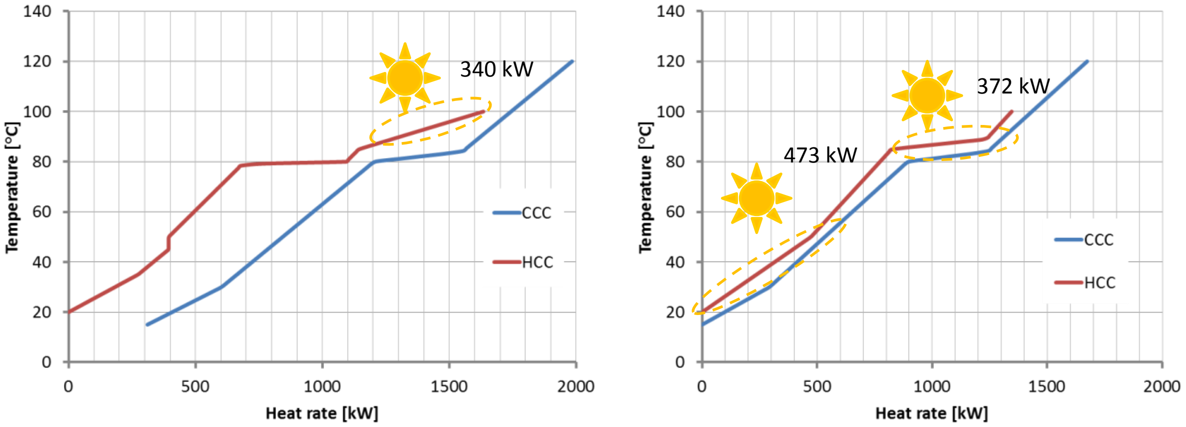


Figure 4-6: CCs including solar heat as hot utility stream (selected and sized with the GCCs from Figure 4-4); ΔT_{min} = 5 °C. Left: 340 kW of solar heat 85/100 °C) added to the hot CC results in a 340 kW decrease of hot utility. Right: Solar heat can be integrated on different temperature levels.

It becomes clear that the tools offered by Pinch Analysis are powerful for first considerations of solar process heat design, however for planning the practical design it is necessary to consider temporal variations and possible thermal storage in detail. Here, the designer has to advance from the pure graphical representation to an optimization-based approach. One possible way to do so is to:

- Design a heat exchanger and storage network for waste heat integration with an algorithm considering the aspect of time,
- Analyze the remaining heat demand and subsequently, and
- Re-design the network for solar process heat integration.

Therefore heat exchanger and heat storage network design algorithms for variable process streams are required to identify and compare process integration measures, and finally translate the thermodynamic potential into practical solutions.

This re-design including solar heat can be integrated as an additional heat source to certain processes and/or storages based on considerations done via the GCC or CC as discussed above. Alternatively a solar heat source can be added as a hot stream and algorithms for heat exchanger and a storage network (HESN) design are activated. Such algorithms may then suggest solar integration points to achieve high energy savings at minimal costs. Based on such combined proposals of heat recovery, solar integration and storage placement, simple system simulations with adequate tools deliver precise information with only slightly more effort in comparison with the graphical analysis. Additionally, parameters such storage sizes and/or operating temperatures can be optimized.

Figure 4-7 shows an exemplary scheme of a heat integration concept including solar heat as utility. System simulations then allow the designing of heat exchangers and storages to achieve best performances. These system simulations include solar heat as a time dependent hot stream (e.g. coming from a solar simulation tool); however they do not simulate the solar thermal system itself.

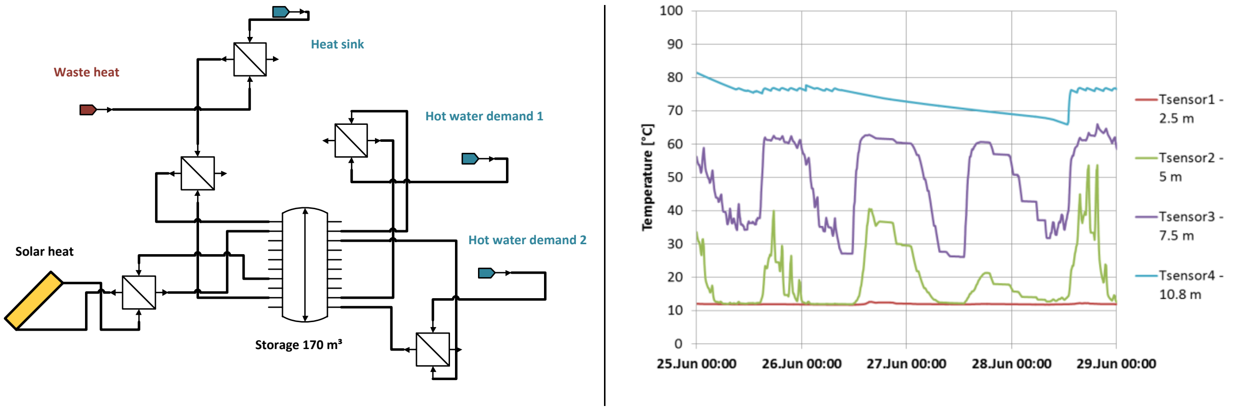


Figure 4-7: Flowsheet in SOCO which can be simulated to evaluate the performance of heat exchangers and storages (on the right) over time; combinations of solar heat and heat recovery can be analyzed.

Within the scope for IEA Task 49 a list of available process integration tools has been collected and their corresponding features for solar heat integration have been evaluated. These tools are summarized in a short overview in Appendix 0. While PINCH and SOCO have started closing the gap for process integration tools with consideration of thermal storages, so far no tools combine process integration algorithms with solar simulations. This will be a future development task.

4.2.3 Workflow for integration of solar process heat

The workflow of the Pinch Analysis based assessment methodology, presented in chapter 3, is depicted in a synoptic way in Figure 4-8. Each iteration loop includes typically 3 steps (so-called AGE methodology of F. Maréchal):

- Analysis of heat integration problem (e.g. by using CCs and GCC)
- Generation of alternative solutions

- Evaluation and comparison of the performances of alternative solutions (scoping and screening).

A fourth step may consist in changing/adapting the problem based on the conclusions of the evaluation step. These steps may essentially be achieved manually by the engineer, e.g. based on simplified models for targeting (if possible), or carried out automatically, by means of optimization algorithms. The workflow does not represent two important input data sets which are 1) the meteorological, technical, economical and legal framework conditions and constraints pertaining specifically to the solar plant (e.g. available area for the solar plant, mechanical load resistance of roofs, subsidies, fraction of diffuse irradiance, etc.); and 2) the framework conditions and constraints related to the industrial plant (existing processes and utility networks, plant layout, financing constraints, energy costs, actual scope for changing some processes, etc.). These opportunities, constraints, and even “KO-criteria” must be identified from the very beginning since they have a strong influence on the scope of the process integration analysis.

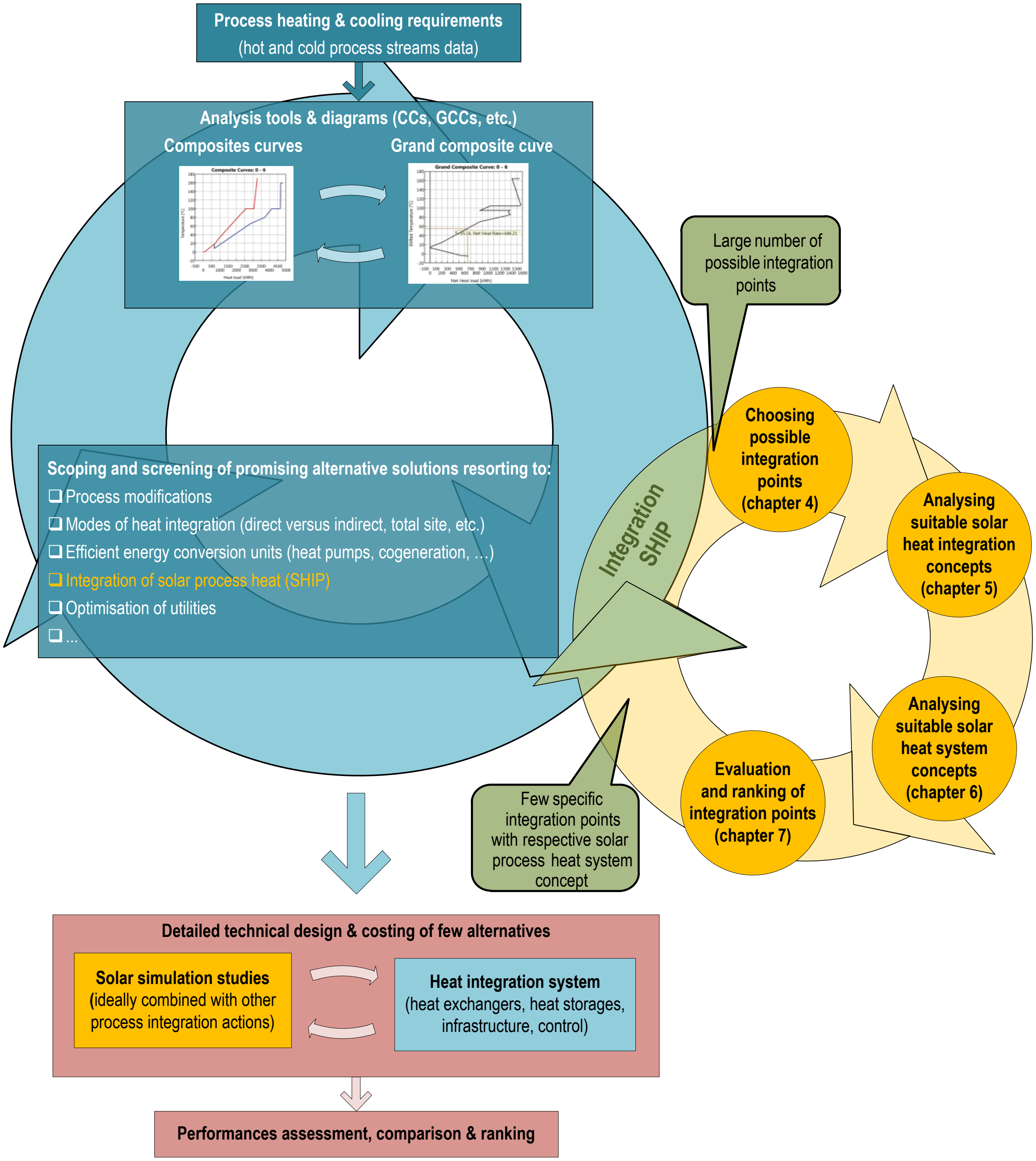


Figure 4-8: Simplified workflow of the Pinch Analysis based methodology extended to the integration of solar process heat

5 Classification of Integration Concepts

Bastian Schmitt

This chapter is extracted from the PhD thesis "Integration of solar heating plants for supply of process heat in industrial companies" (Schmitt, 2014).

Highlights:

- Industrial heat sinks can be classified based on the conventional heat supply to simplify the choice of a suitable integration concept
- Different suitable integration concepts are applicable for integration of solar heat on process and supply level
- On supply level the respective heat transfer medium and integration point directly leads to a possible integration concept
- On process level the category of a heat sink in combination with its conventional energy supply is decisive for the integration concept
- Generalized integration concepts for supply and process level are presented which can be assigned to different types of industrial heat consumers

As shown in chapter 2 there is a multitude of heat consumers in industry that use different installations with various possibilities for thermal energy supply. To ensure a fast identification of a suitable integration concept for solar thermal energy, a classification of industrial heat consumers is presented within this chapter. In general, the following boundary conditions are of particular importance for the integration of solar heat in industrial applications:

- Distinction between supply- and process level
- Heat transfer medium at supply level
- Category of heat consumer at process level
- Conventional way of heating at process level

By considering these four points, classes for the implementation of solar heat can be formed. At supply level the respective heat transfer medium determines the suitable integration concept(s). For a better overview of the multitude of industrial processes, the heat consumers at the process level are assigned to one of the three following categories: "(pre)heating of fluid streams," "heating and maintaining temperature of baths, machineries or tanks" and "thermal separation processes." More or less all thermal driven industrial processes can be assigned to one of these categories. After assigning a process to one of the three categories, the conventional way of heating of the respective process is considered since it is of high importance if a process is heated by external heat exchangers, heating jackets or direct steam injection.

5.1 Classification of Industrial Heat Consumers

Figure 5-1 shows the classification of industrial heat consumers for the integration of solar heat in industrial applications. To find a suitable integration concept for a heat consumer, the level of integration must first be identified. For an integration point at the supply level, a distinction is drawn between steam and liquid heat transfer media. The integration concepts for liquid heat transfer media are valid for hot water, synthetic media, or thermal oils. The different media will only lead to differences in the required heat exchanger type. In principle, the integration concepts for liquid heat transfer media are also valid for air as heat transfer medium.

By using steam, three different integration concepts are possible: solar steam generation (parallel integration), heating of boiler feed water, and heating of make-up water (both serial integration). The parallel integration can be realized directly or indirectly (e.g., with thermal oil or pressurized water). The concepts for serial integration to heat boiler feed water or make-up water differ mainly in the respective temperature level and potential heat recovery measures that have to be considered. Besides the parallel and serial integration of solar heat into conventional heat supply systems with liquid heat transfer media, there is also the possibility to heat storages or cascades that are part of the conventional heat supply system.

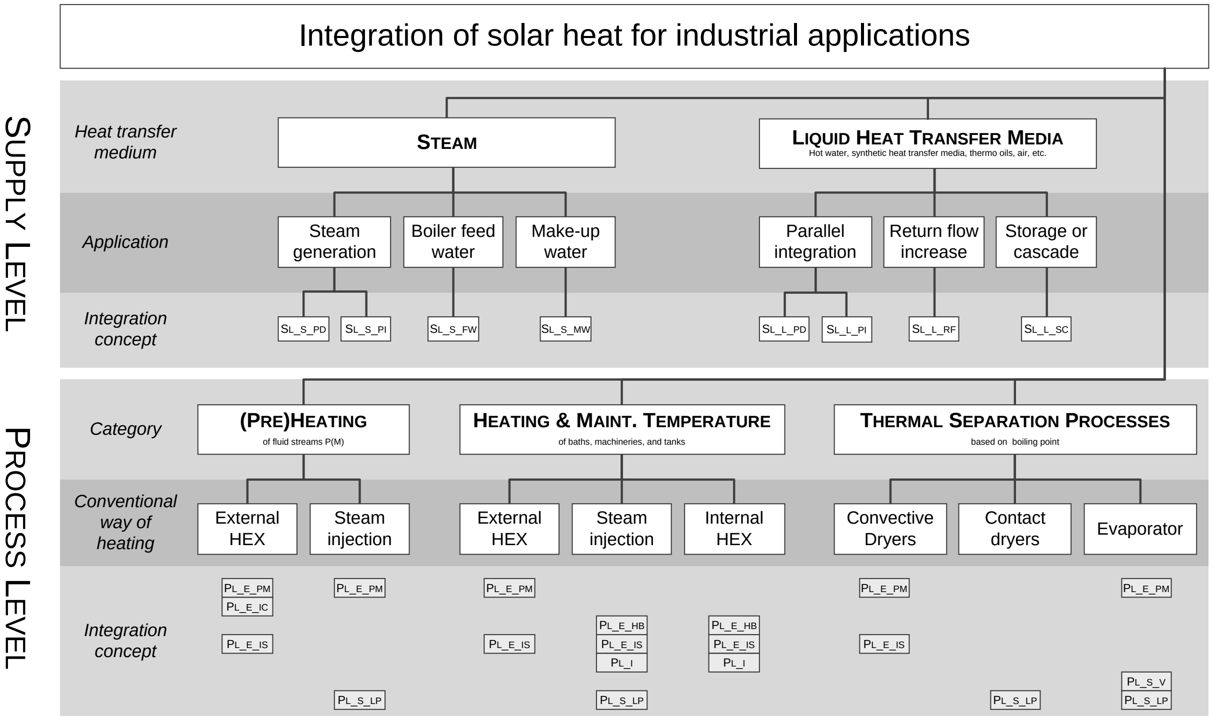


Figure 5-1: Classification of industrial heat consumers for integration of solar thermal energy

At the process level, a first distinction is drawn by the category of the heat consumer. If a process is identified that is suitable for the integration of solar heat within a feasibility assessment (e.g., based on the temperature level and load profile) it should be assigned to one of the three categories "(pre)heating of fluid streams," "heating and maintaining temperature of baths, machineries or tanks" or "thermal separation processes." Afterwards another distinction is drawn by the conventional way of heating. For the category "(pre)heating of fluid streams" two ways of heating are distinguished: external heat exchangers and direct steam injection. Processes assigned to the second category "heating and maintaining temperature of baths, machineries or tanks" can also be heated with internal heat exchangers (this includes heating jackets and -coils, tube bundles, plate coil heat exchangers, electric heating elements and direct combustion). Within the third category "thermal separation processes" it is distinguished between convective- and contact dryers that cover the bulk of all drying installations as well as evaporators that are used for distillation and rectification besides general evaporation processes.

Based on the category of the heat consumer in combination with the conventional way of thermal energy supply, different integration concepts for solar heat can be applied. At the process level, three general classes of integration concepts are distinguished. The first class is the integration of an external heat exchanger that is fed by solar thermal energy. Therefore, four integration concepts are basically possible: integration of an additional external heat exchanger for product or process medium in serial to the conventional one, solar heating of an intermediate hot water circuit, solar driven heat exchanger for external heating of baths, machineries or tanks, and preheating of product or process media input streams. The second class is the integration of an additional heat exchanger surface within baths, machineries or tanks. The third class is solar generation of steam with vacuum or low pressure.

Table 5-1: Overview of integration concepts for SHIP applications

Level of integration	**Heat transfer medium**		**Conventional way of heating**		**Solar heat integration concept**	
Supply Level	S	Steam			PD/PI	parallel integration (direct or indirect)
					FW	heating of feedwater
					MW	heating of make-up water
	L	Liquid			PD/PI	parallel integration (direct or indirect)
					RF	return flow boost
					SC	heating of storages or cascades
Process level			E	external heat exchanger	PM	heating of process medium
					IC	heating of intermediate hot water circuit
					HB	heating of bath, machinery, or tank
					IS	heating of input streams
			I	internal HEX		
			S	steam supply	V	vacuum steam
					LP	low pressur steam

Table 5-1 summarizes all solar heat integration concepts from the presented classification. A short abbreviation exists for every integration concept that includes relevant information. The first two letters define the level of integration. This can be supply level (**SL**) or process level (**PL**). For integration concepts on supply level the third letter defines the conventional heat transfer medium. This can be steam (**S**) or liquid media (**L**). On process level the third letter defines the position of solar driven HEX (**E** for external or **I** for internal) or that steam with reduced pressure is supplied (**S**). The fourth and fifth letter gives further information. E.g. the code PL_E_HB is used for an integration concept on **P**rocess **L**evel that uses an **E**xternal heat exchanger for **H**eating of **B**aths, machineries or tanks.

5.2 Integration Concepts

In the following subchapter, all integration concepts will be briefly introduced and illustrated by a process flowsheet. Figure 5-2 shows the most important symbols for the following flowsheets.

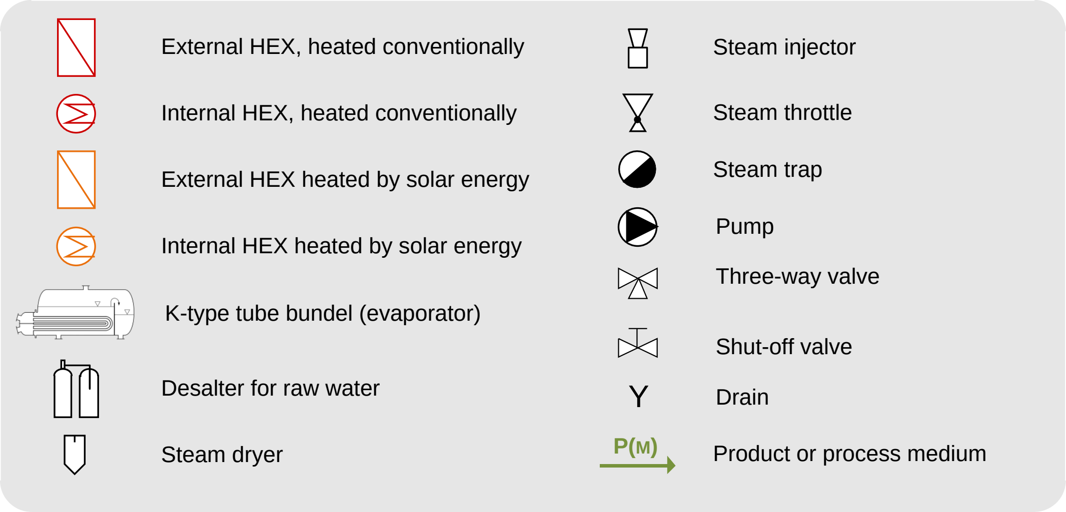


Figure 5-2: Important symbols for integration concepts

5.2.1 Supply level with steam (SL_S)

If high temperature levels are needed for the parallel integration of solar heat (solar steam generation) then suitable collector concepts must be applied. Due to the fact that the required temperature level for parallel integration of solar heat in conventional steam systems is usually above 150 °C, concentrating collectors might be required. Therefore, irradiation data of the location must be taken into account for the choice of the appropriate collector concept.

SL_S_PD – direct solar steam generation

For the integration concept of direct solar steam generation, a steam drum is required that is fed by concentrating collectors. Boiler feed water is fed to the solar heating system and partially evaporated. The water-steam mixture is fed to the steam drum where it is separated. The accumulated water is fed back to the collector loop. In case of sufficient pressure in the steam drum, the steam is fed into the conventional steam circuit (Figure 5-3).

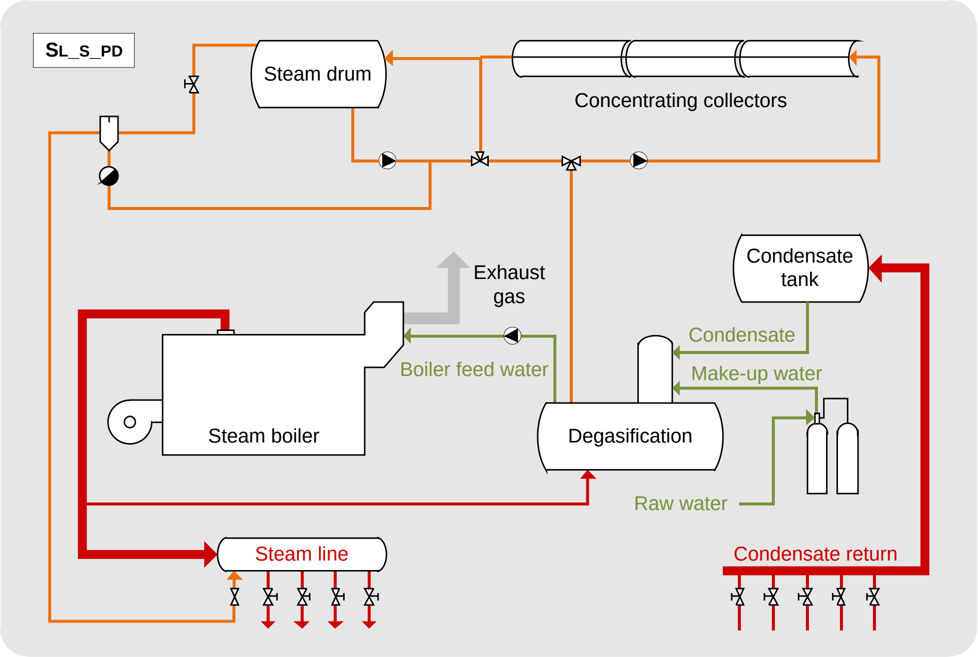


Figure 5-3: Integration concept for direct solar steam generation (SL_S_PD)

While solar steam is fed into the existing circuit, the conventional steam boiler reduces its steam production similar to operation periods with reduced load. The actual loss of efficiency of the steam boiler caused by the solar heating system is influenced by the ratio of installed solar power to conventional capacity, the typical load, and steam boiler performance (scope of modulation). This integration concept was realized with in several demonstration plants.

SL_S_PI – indirect solar steam generation

Regarding the interaction of the solar heating system with the conventional steam supply system, this integration concept is similar to the prior one (SL_S_PD). For this concept, concentrating collectors with pressurized water or thermal oil as heat transfer medium are used to feed a special heat exchanger for evaporation (typically kettle type reboiler). The heat exchanger is operated at the same pressure as the conventional steam system.

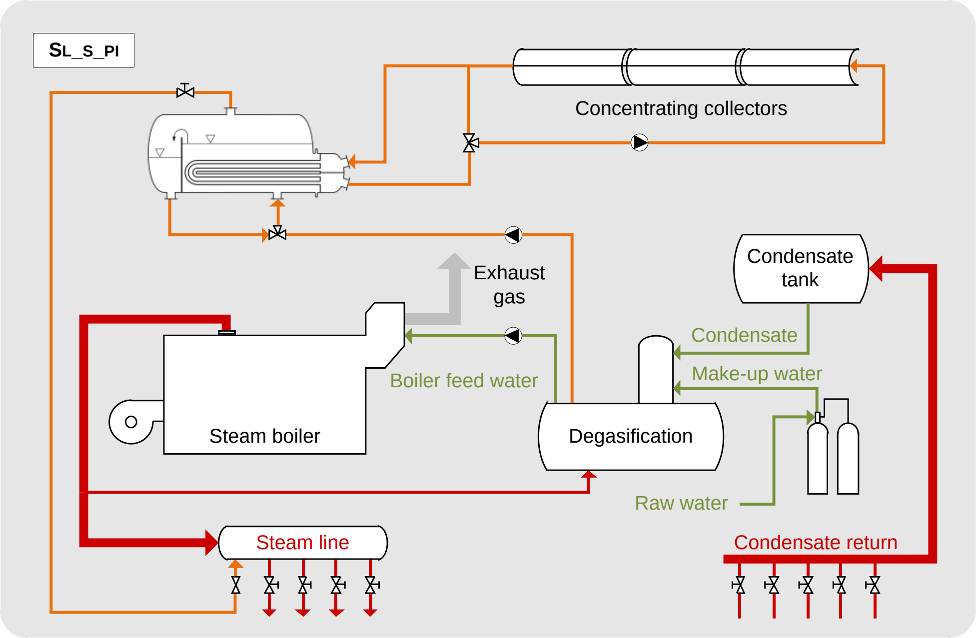


Figure 5-4: Integration concept for indirect solar steam generation (SL_S_PI)

SL_S_FW –solar heating of boiler feed water

The serial integration of solar heat for heating of boiler feed water takes place after degasification. Usually the degasification is operated around 105 °C. The set temperature of boiler feed water depends on the supply pressure of the steam boiler and is usually in the range of 160 - 220 °C (equals 6 to 23 bar). Typically boiler feed water is (or should be) preheated by an economizer before entering the steam boiler (by approximately 30 K). The remaining temperature difference can be supplied by solar heat. Based on the dimensioning of economizers, a solar preheating of boiler feed water prior to the economizer is not always possible.

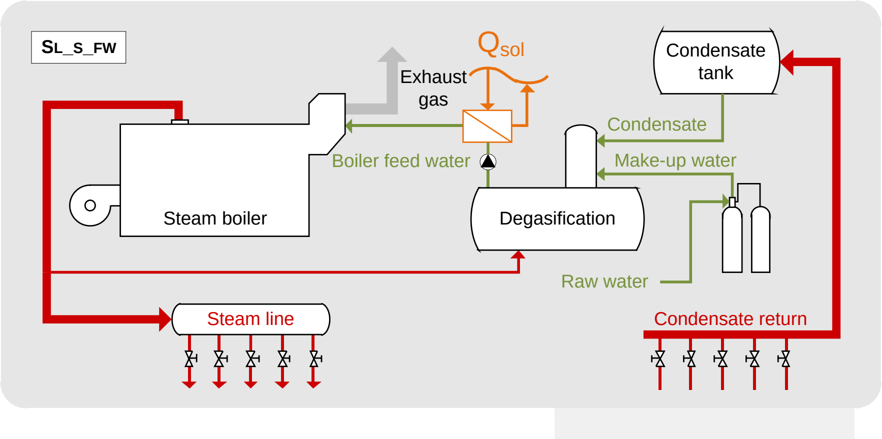


Figure 5-5: Integration concept for preheating of boiler feed water (SL_S_FW)

SL_S_MW – solar heating of make-up water

The last integration concept for steam systems is preheating of make-up water which is required to compensate losses of condensate caused by flash evaporation, blow down and direct steam consumption. Make-up water is fed into the degasification after desalting. In principle, the amount of make-up water can be heated by solar energy prior to degasification. However, several waste heat sources within the boiler house can significantly decrease the potential for implementation of solar heat.

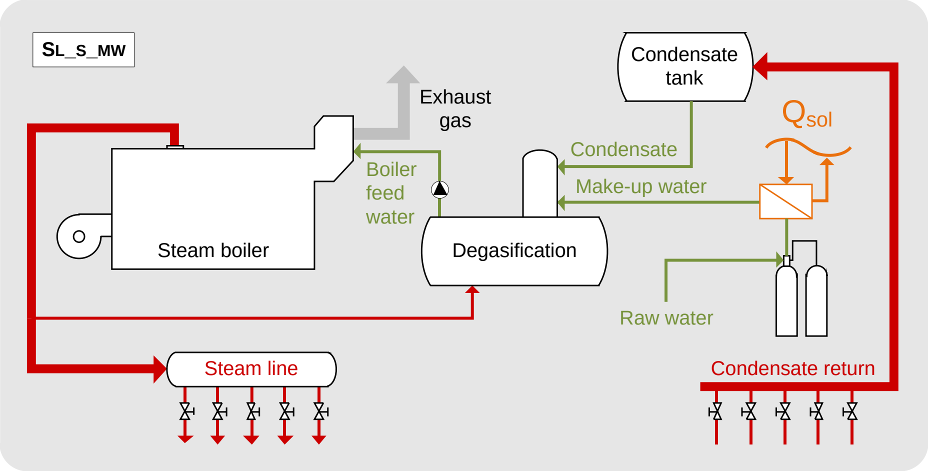


Figure 5-6: Integration concept for preheating of make-up water (SL_S_MW)

5.2.2 Supply level with liquid heat transfer media (SL_L)

For liquid heat transfer media other integration concepts can be applied, as compared to the concepts for steam. Besides the parallel and serial integration of solar heat, it is also possible to heat storages or cascades that are integrated into the conventional heat supply system. Due to the relevance in industry, the main application of these integration concepts is for hot water circuits. However, they can also be applied to synthetic heat transfer media and thermal oils that are typically used for a temperature range of 250 - 400 °C.

SL_L_P – parallel integration

For the parallel integration of solar heat into hot water circuits, the return is divided prior to the conventional boiler and partially directed through the solar heating system and fed back into the flow. Therefore, the control of the solar heating system has to ensure that the return is heated to the required flow temperature. The integration can be realized directly (SL_L_PD) or indirectly (SL_L_PI). For directly integrating the water of the heating circuit directly through the collectors (see Figure 5-7), while a heat exchanger is used for the indirect integration.

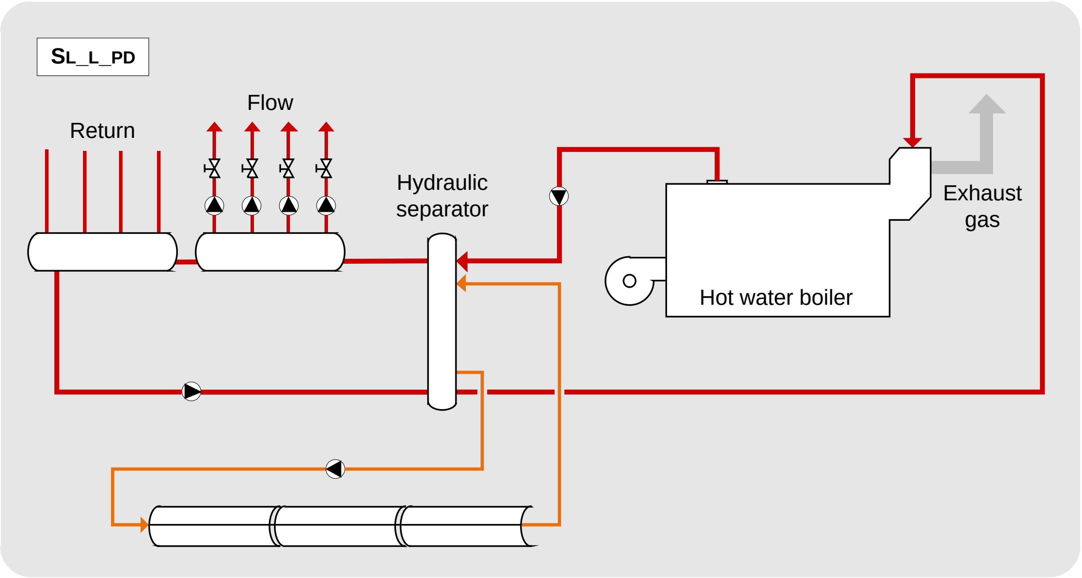


Figure 5-7: Integration concept for direct parallel integration at supply level with liquid heat transfer media (SL_L_PD)

Sometimes also combined heating circuits can be found in Industry that use steam as primary heat transfer medium to generate hot water as secondary heat transfer medium via heat exchangers or hot water cascades. This also can be vice versa in companies with little low pressure steam demand. In this case hot water is used as primary heat transfer medium and produces steam via hot water in a small steam drum.

SL_L_RF –solar return flow boost

The serial integration of solar heat is similar to integration concept SL_L_PI, with the difference that the return is preheated. Therefore, no fixed set temperature has to be supplied by the solar heating system. Return line heating might not be desired by the industrial plant operator if the efficiency of the conventional heating system is affected in a negative way (e.g., condensing boiler, CHP or district heating).

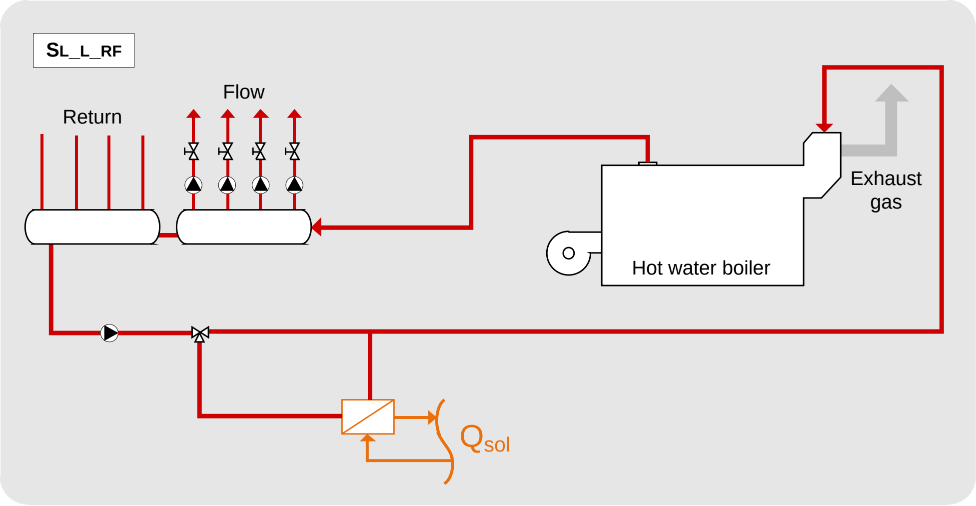


Figure 5-8: Integration concept for serial integration at supply level with liquid heat transfer media (SL_L_RF)

SL_L_SC –solar heating of storages or cascades

There are many different types and connection possibilities for hot water storages in industry. There are storages with fixed or variable volume that are fed with hot water or buffer storages that are energetically charged and discharged. Based on the actual number of storages and their configuration solar heat can be used to preheat input streams or to maintain the temperature of the storage. Additionally, hot water cascades can be supplied with solar heat. Usually the hot water return is fed into a cascade and heated by the injection of steam. The integration concept for hot water cascades is similar to SL_L_RF since the return flow is preheated before entering the cascade.

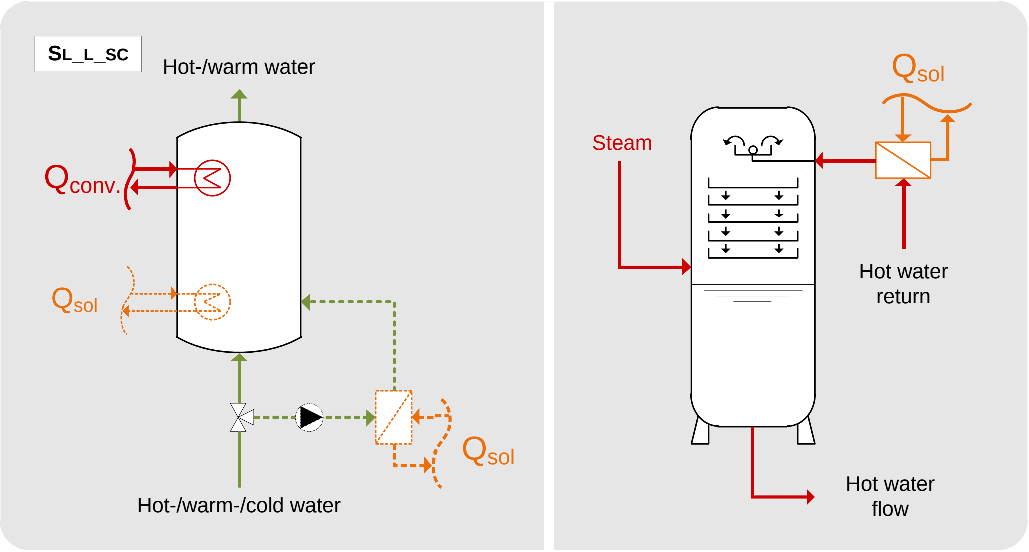


Figure 5-9: Integration concept for solar heating of hot water storages or cascades (SL_L_SC)

The concepts presented are not limited to the integration of solar heat. The integration concepts solely recommend a suitable interface to implement an additional heat source within the existing system. In principle, other heat sources such as cogeneration, heat pumps, or high temperature waste heat can be used. For example, integration concept SL_L_RF can also be applied to heat pumps. In this case, the return of the conventional heating circuit is heated by a heat pump to the required flow temperature. Therefore, a heat source at a lower temperature level (e.g., solar or waste heat) is required (see Figure 5-10).

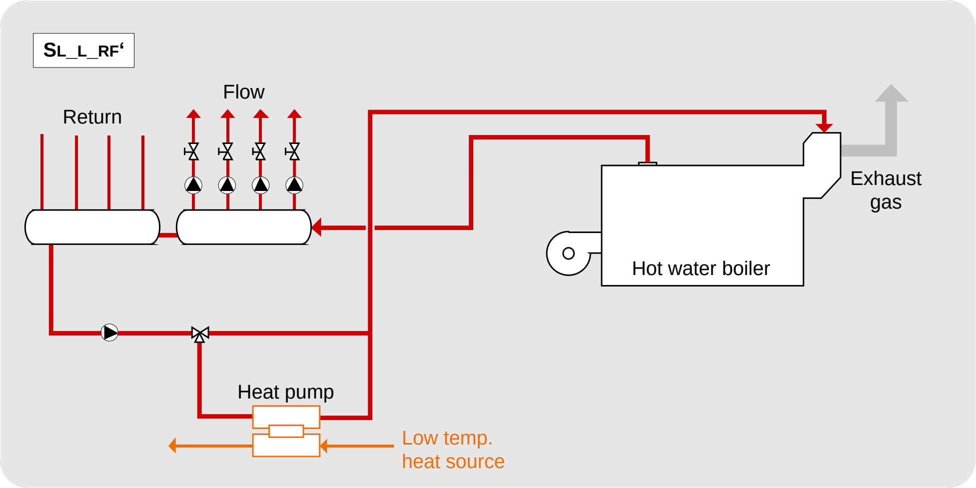


Figure 5-10: Integration concept SL_L_RF adapted for a heat pump

5.2.3 Process level external heat exchanger (PL_E)

At process level, three general classes for solar heat integration are distinguished. The first class is the integration of an external heat exchanger supplied with solar energy. For this class, four different concepts can be applied: serial connection of an external HEX for heating product or process media (PL_E_PM), serial connection of external HEX for heating of intermediate hot water circuit (PL_E_IC), integration of external HEX for heating of bath, machinery or tank (PL_E_HB) and integration of external heat exchanger for heating of input streams (PL_E_IS). These concepts are introduced below.

PL_E_PM - external HEX for heating of product or process medium

This integration concept is basically the easiest since an additional solar driven heat exchanger is installed in serial to the conventional heat exchanger to heat a product or process medium (e.g., water, lye, fruit juice, etc.). It can be applied to all three categories of heat consumers “(pre)heating of fluid streams”, “heating and maintaining temperature of baths, machineries or tanks” and “thermal separation processes.” The serial integration of a solar driven heat exchanger can be realized in a way that only part of the entire product or process medium stream is heated up and hence heat exchanger surface, pump, and pipe dimensions can be kept small.

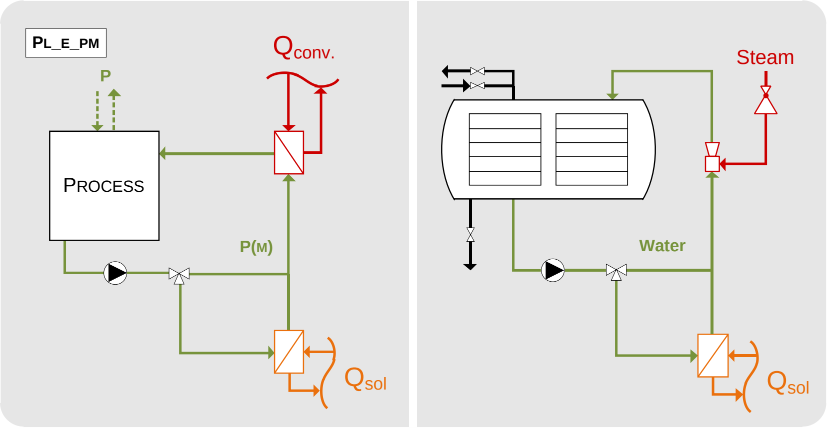


Figure 5-11: Integration concept for solar heating of product or process media with external heat exchanger (PL_E_PM). General integration flowsheet (left) and illustrated by sterilization process with autoclave (right).

PL_E_IC - external HEX for heating of intermediate hot water circuit

Within the food and beverage sector intermediate, hot water circuits can be used to heat sensitive products. Therefore, the conventional heat transfer medium is used to heat this hot water circuit to a temperature slightly above the required set temperature of the product (e.g. pasteurization of milk). In these cases integration concept PL_E_IC can be applied. This concept equals more or less PL_E_PM. Due to the fact that solar heat is used to heat water, the integration is usually easier in case of the required heat exchanger or safety installations, compared to the direct solar heating of products. If a process is directly heated by a conventional hot water circuit, the integration concepts PL_E_IC and SL_L_RF can be combined. Therefore, the return is preheated with solar energy directly behind the process since the average temperature of the central return line is usually higher.

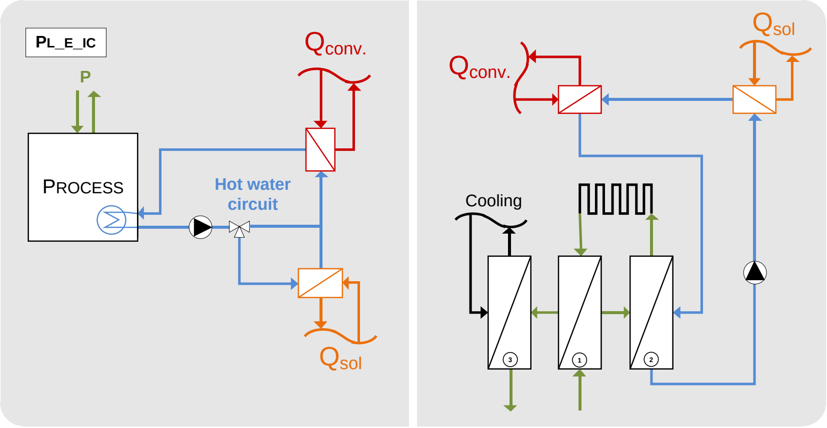


Figure 5-12: Integration concept for solar heating of intermediate hot water circuits with external heat exchanger (PL_E_IC). General integration flowsheet (left) and illustrated by pasteurization process with multi zone plate heat exchanger and external heating zone (right).

PL_E_HB - external HEX for heating of bath, machinery, or tank

This integration concept is used to heat baths, machineries, or tanks via an additional external heat exchanger. Therefore, the product or process medium is drawn from the bath, machinery, or tank, heated by solar energy and fed back. It is crucial for this integration concept to identify a suitable position or point in time within the process where the temperature of the product or process medium is relatively low. Else this concept would lead to a parallel integration of solar heat to the conventional heat supply. If the product or process medium must be kept in a very narrow temperature range (due to operational issues), the resulting temperature difference for solar heating might be very small.

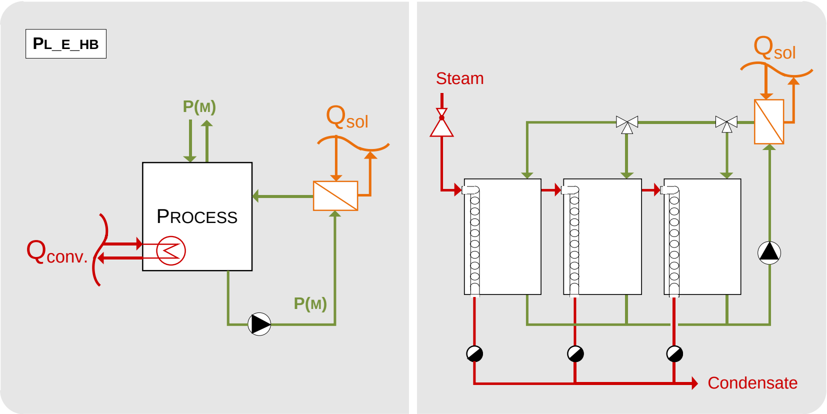


Figure 5-13: Integration concept for solar heating of bath, machinery, or tank with external heat exchanger (PL_E_HB). General integration flowsheet (left) and illustrated by electro plating process heating with internal plate coils (right).

PL_E_IS - external HEX for heating of input streams

The fourth possibility for integration of external heat exchangers is solar heating of input streams. Many processes require continuous or batch feed-in of product or process media streams, for example, the feed-in of fresh water to compensate for evaporation losses or fresh air for drying applications. Based on the specific process, it is reasonable to preheat these input streams. The process flowsheet for this integration concept is shown in Figure 5-14. The dashed lines indicate possibilities for the conventional heating of the existing process. Additionally, the integration concept is illustrated with an example. The displayed scalding bath for chicken slaughtering is conventionally heated by direct steam injection. Based on water discharge from carcasses and evaporation losses, a significant amount of fresh water is fed to the scalding bath, which can be preheated by solar energy. It is possible that this integration concept can be combined with PL_E_PM and PL_E_HB.

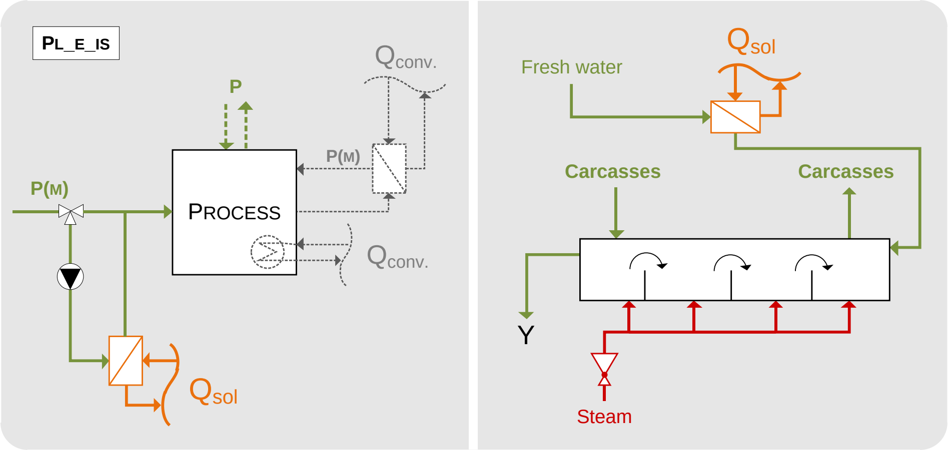


Figure 5-14: Integration concept for solar heating of input streams with external heat exchanger (PL_E_IS). General integration flowsheet (left) and illustrated by scalding process for chicken slaughtering heated via direct steam injection (right).

5.2.4 Process level internal heat exchanger (PL_I)

Besides the integration of external heat exchangers, processes can be supplied with thermal energy by internal heat exchangers. Therefore, the second class for the integration of solar heat on process level is the integration of an additional heat exchanger within baths, machineries, or tanks (PL_I), thus used for the category "heating and maintaining temperature of baths, machineries, or tanks". Usually, the additional solar driven internal heating surface is installed in parallel to the conventional heat source. For this concept it is important to consider the available space in the process equipment since it is usually limited due to the treated product (e.g. metal parts) or components (e.g. stirrers, strainers, etc.).

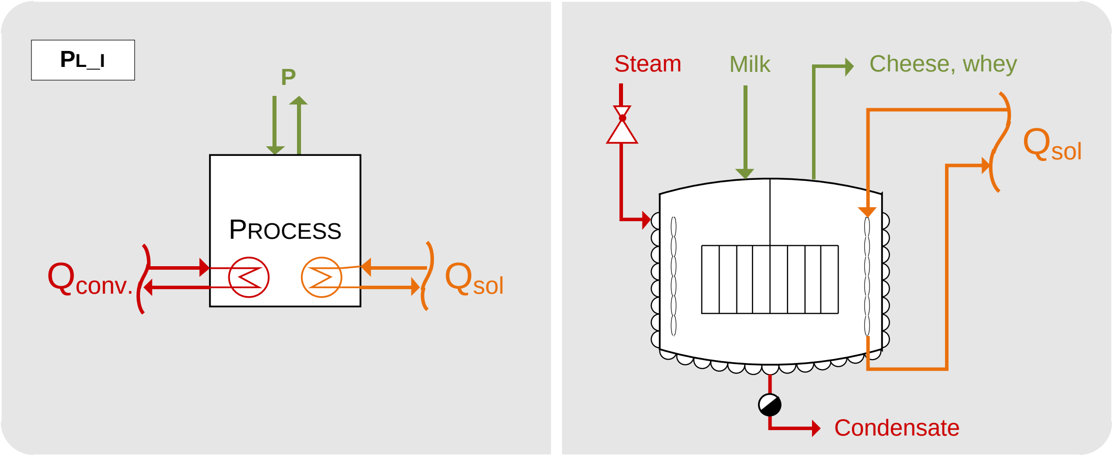


Figure 5-15: Integration concept for solar heating of bath, machinery or tank with internal heat exchanger (PL_I). General integration flowsheet (left) and illustrated by curd vessel for cheese production heated with conventional heating jacket and additional solar driven dimple plates (right).

5.2.5 Process level steam supply with reduced pressure (PL_S)

The third class for the integration of solar heat covers solar steam generation with reduced pressure. Therefore, two concepts can be applied to supply steam with vacuum (PL_S_V) or with low pressure at a temperature range of 110 - 135 °C (PL_S_LP).

PL_S_V - solar steam generation at vacuum

Solar steam generation within a vacuum can be applied for numerous evaporation processes e.g. in food and beverage industry, since typical process temperatures are in the range of 40 - 80 °C. Therefore, an evacuated storage with a conventional heat exchanger is required. The condensate from evaporation process is preheated by solar energy and fed into the evacuated storage. The evaporated condensate is fed back into the evaporation process.

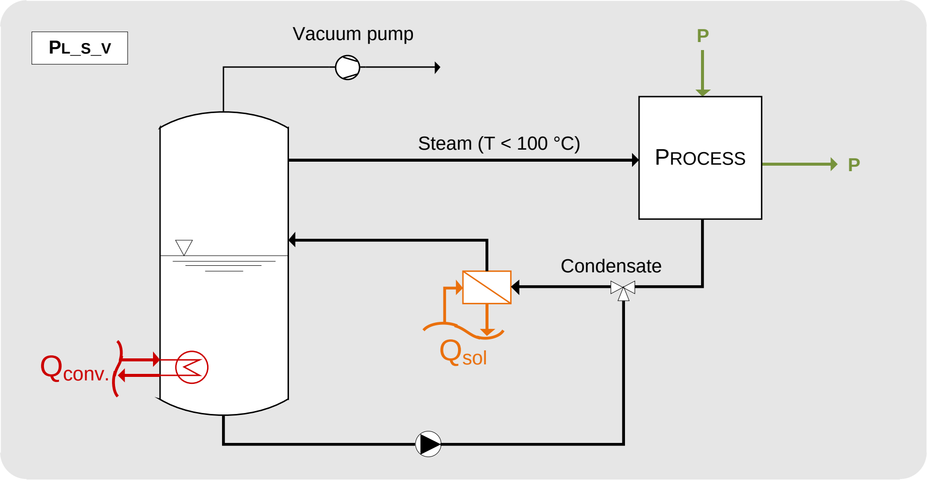


Figure 5-16: Integration concept for solar steam generation with vacuum for heating of evaporators (PL_S_V)

PL_S_LP - solar steam generation at low pressure

For solar steam supply with reduced pressure of 1.5 - 3 bar (according to 110 - 135 °C) a kettle reboiler is required that is supplied with solar heat. Feed water or condensate is fed into the reboiler, evaporated and used to heat the process. Therefore, the conventional steam demand for injection heating is reduced. Based on the required installations this integration concept is similar to SL_S_PI on supply level. The only difference is the reduced temperature level compared to conventional steam systems in Industry. Therefore, this integration concept can also be applied in moderate climatic conditions.

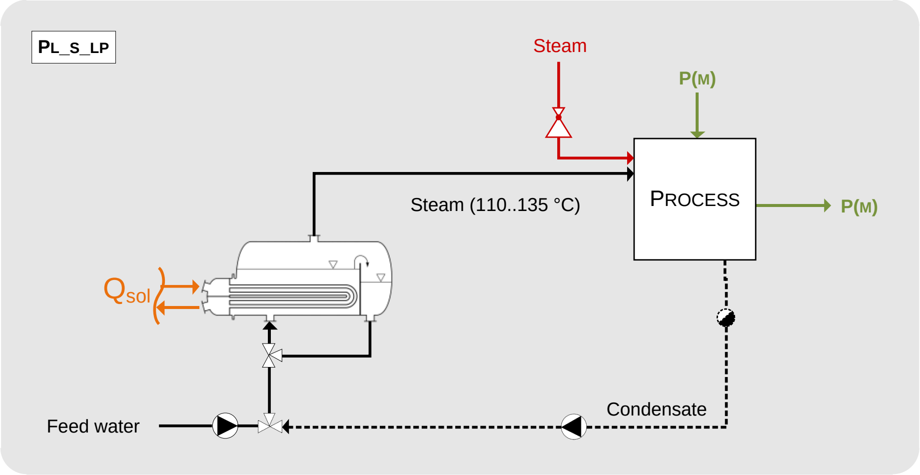


Figure 5-17: Integration concept for solar steam generation with reduced pressure for direct steam injection (PL_S_LP)

5.3 Application of Classification

For the integration of solar heat at the supply level, the respective heat transfer medium and integration point directly leads to a possible integration concept. In contrast, it is feasible that several integration concepts can be integration points at the process level. In this case, the real boundary conditions of the chosen process can lead to a reduction of possible integration concepts. This is illustrated in the scalding process (see Figure 5-14). For processes in the category "heating and maintaining temperature of baths, machineries, or tanks" that are heated by direct steam injection, four integration concepts are proposed by the classification: external bath heating PL_E_HB, heating of input streams (PL_E_IS), internal heat exchanger (PL_I) and steam supply with low pressure (PL_S_LP). In this case, a possible approach to choose the best integration concept is to check the requirements of the considered concepts starting with the lowest temperature demand. For the scalding process this would be PL_E_IS. If large quantities of fresh water are supplied to the scalding bath, this integration concept offers the possibility to integrate solar heat at the lowest temperature level. If for technical reasons cold water has to enter the bath integration concept (e.g., to cool down the product) then PL_E_IS should be excluded. Based on the temperature level integration concepts PL_E_HB and PL_I should be considered next. The feasibility of these concepts are influenced by the possibility to remove the process medium for heating by an external heat exchanger, or the available space for an internal heat exchanger within the bath. Regarding the effort for integration, concept PL_S_LP (solar steam supply with reduced pressure) is much easier, since there is no interference in the existing process. However, the highest temperature has to be supplied by the solar heating plant for this concept. It might also be possible to combine two integration concepts. If for example the fresh water input stream is fed discontinuous into the bath that can be preheated, it might be reasonable to combine integration concepts PL_E_HB and PL_E_IS. Thereby, the bath can be heated by an external heat exchanger during periods without fresh water input.

6 Classification of Solar Process Heat System Concepts

Annabell Helmke, Stefan Heß

Highlights Chapter 6

- SHIP systems are subdivided into five characteristic sections.
- Understanding characteristic integration temperature requirements are essential for the design of a well-suited SHIP system.
- SHIP requires dedicated storage charging, interconnection and discharging concepts, which are interlinked and highly influence the system performance.
- Simple, generalized SHIP system concepts can be assigned to the integration concepts given in Chapter 5. This provides a starting point for detailed system design.

The high variety of industrial and commercial processes leads to a large number of possible integration points for solar heat. In Chapter 5 several integration concepts for solar heat on process and supply level have been described. **This chapter helps to identify suitable solar thermal process heat (SHIP) system concepts for the integration concepts discussed in section 5.2.** First, the decisive temperature levels for SHIP integration and system design are discussed, and then the SHIP systems are divided into five characteristic subsections. For each subsection, the benefits and drawbacks of the existing hydraulic concepts and components are briefly discussed and concepts for solar steam generation are given. To offer practical help on SHIP system layout, seven exemplary SHIP system concepts for common applications are provided. Finally, a summarizing table provides the link between the integration concepts of section **5.2** and the exemplary SHIP systems.

In general, the SHIP integration concept and system design must meet the requirements of the supported integration point in terms of heating rate, temperature level, etc. At the same time, SHIP systems must be designed for high system utilization rates (annual efficiency of solar irradiance conversion into supplied process heat) that allow for low solar heating costs. The optimal collector and storage types for a certain application as well as their dimensions vary with required temperatures, load profiles, and plant location. These parameters highly influence the hydraulic concept and the overall system control strategy.

6.1 Subsections and Temperatures

The subdivisions in Figure 6-1 and Figure 6-2 are intended to structure the components and hydraulic concepts discussed within this chapter. Important temperature terms for SHIP integration are explained.

The SHIP system is connected to the conventional plant via the integration point. This integration point can be a heat exchanger, a valve or simply a T-piece. In low-temperature SHIP systems with storage, usually all five sections can be distinguished. At systems without storage, as for example, at direct solar steam generation, only the subsections “collector loop” and “integration point” are found.

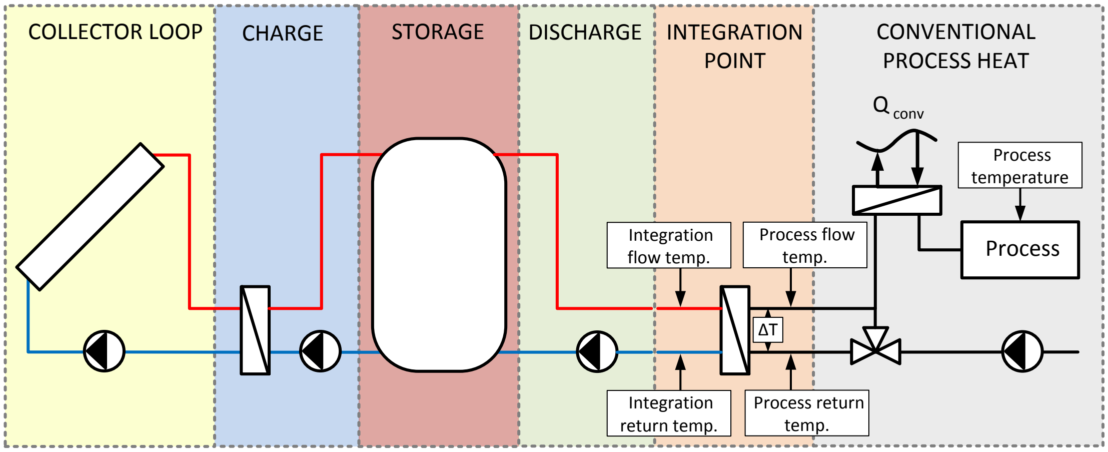


Figure 6-1: SHIP system for pre-heating with five subsections supplying an industrial heat consumer. The integration concept exemplary shown is PL_E_PM, i.e. on process level an external heat exchanger heats a process medium (see Figure 5-11).

The process shown in Figure 6-1 is supplied e.g. with fresh water in an open loop, so process return and thus integration return temperature are constant. The maximum integration flow temperature is the temperature level needed to maintain the set process temperature. The SHIP system is usually pre-heating, but in case the maximum integration flow temperature can be provided, the conventional heating Q_{conv} is switched off.

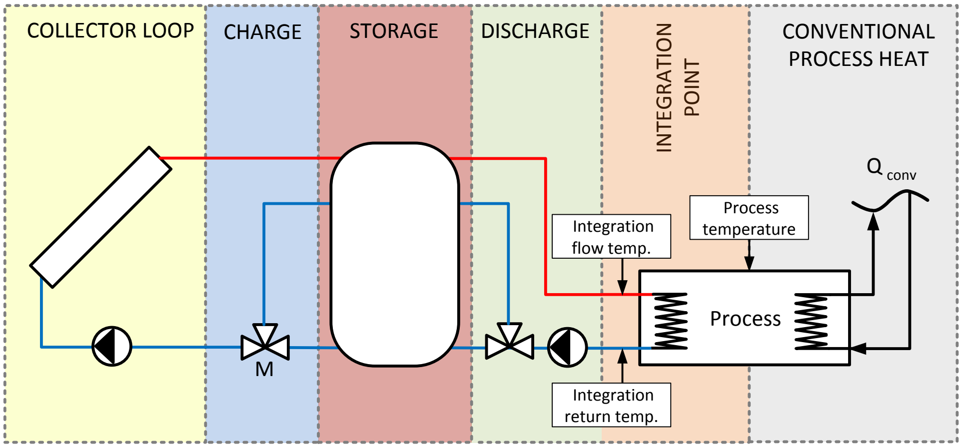


Figure 6-2: SHIP system for heating purposes. The integration concept exemplary shown is PL_E_HB, i.e. on process level an internal heat exchanger heats a bath filled with the process medium (see Figure 5-11).

In Figure 6-2, the temperature of the process medium is kept constant. Thus, a set integration flow temperature is required, which results in a constant integration return temperature. Below the set flow temperature; no solar heat can be transferred. The conventional heater can only be switched off at times when the SHIP system constantly supplies the required heating power.

When transferring solar heat to an industrial plant, distinguishing between two characteristic integration temperature levels is very important, since these temperatures are decisive for the design of a SHIP system. Most important is the **integration return temperature,** which is the return temperature from the integration point to the SHIP system, determined by the medium to be heated. The integration return temperature can be constant (e.g., caused by cold water from the grid) or varying (e.g., return flow boost of a pressurized water heating network with varying thermal load). The lower the integration return temperature, the higher the potential solar gains, since low integration return temperatures result in low mean collector temperatures and thus in high collector and system efficiencies.

The other important temperature is the **integration flow temperature**, which is the solar feed temperature to the integration point determined by the desired final temperature of the medium to be heated. Here, three different requirements are possible. In solar pre-heating systems, a **maximum** flow temperature is specified. In this case, the solar supply temperature varies according to the available solar gains and solar heat is transferred whenever a positive temperature lift of the medium to be heated is possible. If a certain constant flow temperature is needed, a **set** flow temperature must be specified. In this case, the SHIP system will be controlled to supply only this set temperature level. It will not be discharged if either the solar gains are too low to achieve the temperature or the storage temperature is so high that the discharging device cannot mix the set temperature level. Finally, **minimum** flow temperatures are also possible. In this case, the SHIP system is only discharged if this temperature level is provided or exceeded. In the last two cases, the temperatures of the collector loop and storage are higher than in pre-heating systems. Thus, the solar gains for such applications are usually lower.

In solar pre-heating (also known as return flow boost) systems, the **process flow temperature** will be limited to a maximum temperature, while every positive temperature lift of the flow is possible. For a solar heating system, a set integration flow temperature together with a range of temperature tolerance will be specified in the control settings to maintain the temperature of the process medium.

On the process side, the process temperature may influence the integration return temperature and integration flow temperature depending on the integration concept. In solar heating systems, the process temperature directly impacts on the integration return and integration flow temperature. In solar pre-heating systems, however, the process return and process flow temperatures are most relevant. They can clearly differ from the process temperature when the process is heated over an intermediate heat transfer medium.

6.2 System Components and Hydraulic Concepts

In the following, the main components of SHIP systems are briefly described. Hydraulic designs for collector loop, storage charging, storage interconnection and storage discharge are given as well as schemes for solar steam generation.

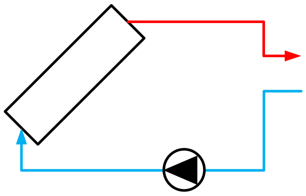
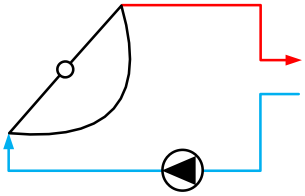
6.2.1 Collector loop

A solar thermal collector converts solar irradiance into heat. The collector loop transfers this heat to either a heat exchanger, a buffer storage, or directly to the solar heat integration point. A collector loop consists of pump(s), safety valve, non-return valve, expansion vessel, and a pump control unit using signals of temperature sensors. For simplification, not all of these components are shown in the following.

Collector types

The selection of a collector type depends on the integration temperature levels, the process medium, and the local annual irradiation characteristics. For integration temperatures below 100 °C, generally non-tracked and usually non-concentrating or low-concentrating collectors are sufficient. For temperatures above 160 °C, usually concentrating collectors tracking the sun must be applied. Within the temperature range between 100 °C and 160 °C both collector types can be technically suitable. For a specific site and application, the technology selection must be based on the lowest heat generation costs during service lifetime. Below, the two main collector categories and most common collector types are given.

Table 6-1: Collector types

Description	Schematic concept
Non-tracking collectors: Stationary or seasonally tilted • Standard flat-plate collectors • Evacuated flat-plates • Evacuated tube collectors • Low-concentrating stationary collectors • Air collectors	
Tracking collectors: Linear or two-axis tracked • Parabolic trough collectors • Linear Fresnel collectors • Collectors with tracked receiver • Parabolic dish • Heliostats with central tower receiver	

Sizing and operation

The collector **field size** depends mainly on the desired solar fraction (share of the total thermal loads to be supplied by the solar) and on the available collector mounting area. It also depends on the system utilization ratio, which is influenced by the collector size and type, storage volume size and type, and the required feed temperatures and heat transfer rates at the integration point(s). Non-tracking collector fields usually work at mass flows of around 30 kg/(m²h), but depending on the collector interconnection, the desired temperature lift and control, the mass flows can be highly different from this.

The **collector fluid** type depends on the collector type and on the risk of freezing, but can also be influenced by the heat transfer fluid (HTF) or the process medium at the integration point. If this is air or steam, it is common to supply the heat directly via injection to the process, so collector- and heat transfer medium can be the same. But often, collector fluid and HTF differ from each other and are separated by heat exchangers. If freeze protection is necessary, non-evacuated collectors usually use a mixture of about 60 % water and 40 % glycol in the collector loop. A charging heat exchanger transfers the heat to the storage medium, which is usually water. For indirect steam production with focusing collectors, water or thermal oil is used and the HTF evaporates at the integration point, which is an evaporator in this case. For direct steam generation within the collector's absorber tubes, a steam drum with steam separator is needed. Summarizing, the media commonly used in collectors are water-glycol-mixture, (pressurized) water, steam, thermal oil, and air.

Due to overheating at times with high irradiance and no heat demand, or due to malfunction e.g. of the collector pump, **stagnation** can occur. This phenomenon describes the full or partly evaporation of the heat transfer fluid inside the collector due to overheating, which can cause considerable damages to the collector loop components and the fluid itself. Therefore, stagnation protection should be an integral part of every solar heating system design and control strategy. There are different active (need of electricity supply) and passive options.

Selected passive (no electricity demand) and active measures for stagnation protection are:

- Collectors and collector loops with good self-emptying behavior, in which evaporated water steam collects in the collector header and presses the water-glycol mixture out of the collectors, so that the glycol is not thermally damaged. A non-return valve controls the direction of steam dissipation and an auxiliary vessel protects the expansion vessel
- Passive evaporative cooler in the collector loop
- Drain back system (stagnation and freezing protection)
- Active cooler in the collector loop
- Defocussing of tracked collectors

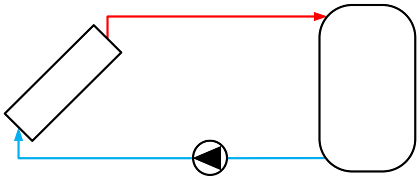
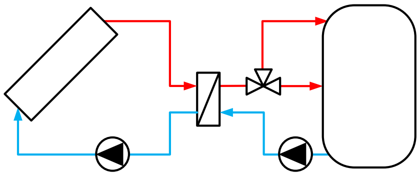
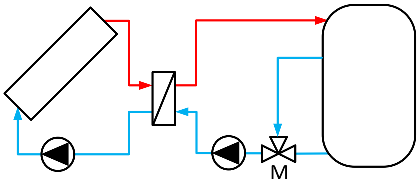
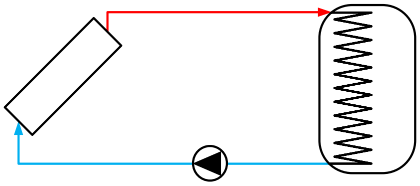
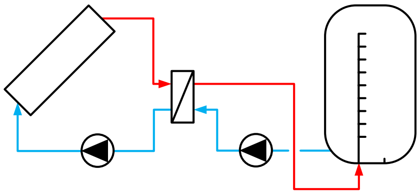
Detailed information on stagnation and stagnation handling can be found in (Frank E. et al., 2014).

The collector loop **control** manages the operation of the pumps and detects stagnation or malfunctions. Dependent on collector type and system design, it is either necessary or beneficial to circulate the HTF through the collectors only and bypass the heat transfer unit (e.g., charging heat exchanger). This allows for the capacity of the collector loop to be heated and a certain temperature level reached or stabilized before starting the heat (mass) transfer to the storage (or HTF or process medium). Heat transfer from the storage to the collector loop is always to be avoided.

6.2.2 Storage charging

Whenever the load profiles at the connected integration points require a storage concept then suitable storage charging and discharging strategies must be applied. In SHIP systems, the most common concept is the storage charging via an external plate heat exchanger because it offers high heat transfer rates. This is sometimes combined with stratification devices, for example, a three-way valve that controls (dependent on the charging temperature) the inlet height of the charging mass flow. The stratification within the storage should not be destroyed. If certain set integration temperatures are required, mixing mass flows from different storage height can control the inlet temperature to the collector field. This way the storage is not mixed during charging and constant high collector outlet temperatures can be reached. The following Table 6-2 shows five different storage charging strategies.

Table 6-2: Storage charging strategies (last two concepts are not common for SHIP systems).

Description	Schematic concept
Direct charging without heat exchanger • Cheap • Robust • Collector fluid is storage fluid • Discharge of storage by solar loop difficult to avoid	
External heat exchanger with **stratification** valve • Prioritizes high collector loop efficiency • Stratification valve controls storage inlet height by charging flow temperature (optional) • Different media in collector field and storage	
External heat exchanger with **mixed charging return flow** (M = mixing valve) • Prioritizes fast process supply • Beneficial for higher integration temperatures • Charging return flow is mixed to reach set charging temperature • Variable speed pumps can be applied to reach target storage charging (and process supply) temperature • Total volume only charged if load is covered • Storage acts as hydraulic separator, when process return flow also has a stratified inlet	
Internal heat exchanger (not common for large systems) • Reduced piping heat losses • Costly heat exchanger	
Heating lance (not common for large systems) • Internal stratification device • Costly • Good stratification	

6.2.3 Solar buffer storages

Storage of solar heat allows to buffer mismatches between the demand heat load profile at an integration point and the availability of the solar resource. The decision if a thermal storage is installed depends on the cost/benefit ratio as well as on the control and stagnation concept of a SHIP system. For low-temperature systems in applications with five working days per week, a thermal storage is recommended. Focusing systems for steam generation usually operate without storage.

Storage types

The desired integration flow temperature and the collector medium influence the storage type. There are two main concepts of heat storage: **sensible heat storages** with water, thermal oil or solid media, and **latent heat storages** with chemical or PCM (phase change material) medium. Sensible heat storages are widely used, while latent storages, despite their much higher heat capacity per volume, are still in an early stage of development. For process heat applications, storages with reduced heat losses e.g. due to increased insulation thickness or vacuum insulation are available. The following list gives an overview of the most common storage types and their characteristics.

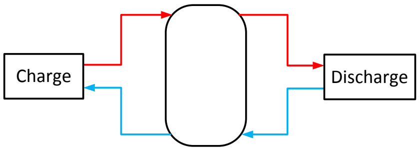
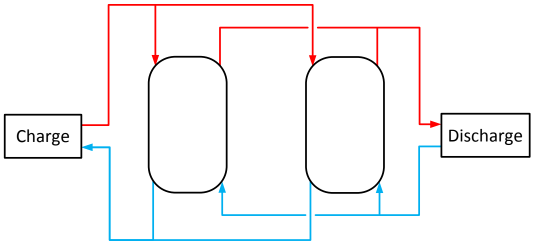
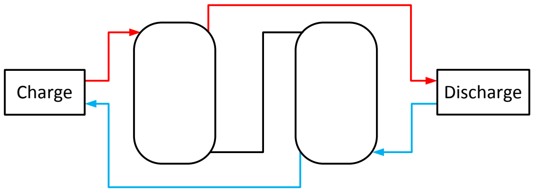
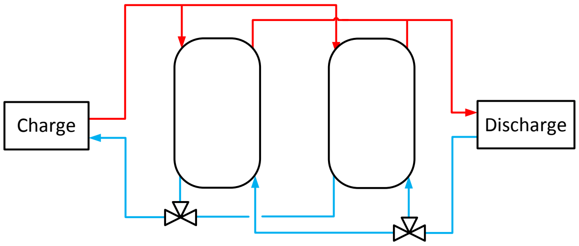
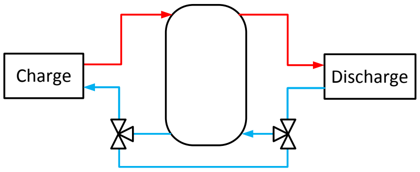
- Sensible fluid with non- or very low pressure: Most common and cheap technology, medium usually water, operation up to 95 °C, good stratification.
- Sensible fluid pressurized: Used to extend operation temperature to above 95 °C, costs pressure dependent, good stratification.
- Sensible solid stage: Cheap materials such as rock-beds or concrete can be used, suitable for air collectors without a heat exchanger.
- Latent: High storage capacity per volume, material selection allows adjustment of storage temperature level, lower thermal losses per kWh than sensible storage, often costly.
- Chemical: High storage capacity per volume and lowest heat losses, heat conduction for charging and discharging can be challenging, expensive technology and still in prototype stage.

Sizing, interconnection, and management

The storage size is usually indicated in l/m^2 of collector aperture area. It is determined by the heat demand profile and the location, but also by the integration point and maximum or set supply temperature. Typical values for low temperature SHIP systems in Europe are about 50 to 70 l/m^2 (Central Europe) to about 70 to 120 l/m^2 (Southern Europe). These values are very indicative and highly dependent upon the integration of the flow and return temperature levels. The storage volume of SHIP systems should always be optimized using system simulations.

If room height or available space for buffer storage is limited then the total storage volume may have to be divided into several storages. For this purpose, different types of interconnections exist. They should be carefully selected because minor mistakes in storage interconnections can lead to insufficient storage stratification or undesired flow distributions. More than two parallel storages should be avoided because it is difficult to ensure the uniform flow. In general, storage management should aim to activate storage volume at times without process heat demand since storage always induces exergy losses and heat losses over time. The following Table 6-3 gives an overview on the benefits and drawbacks of different storage interconnection concepts.

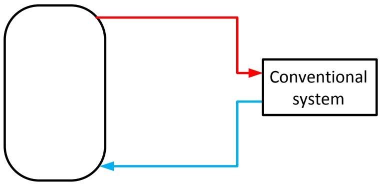
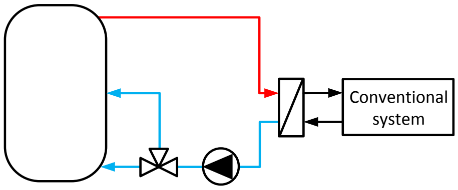
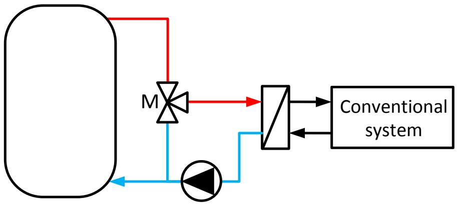
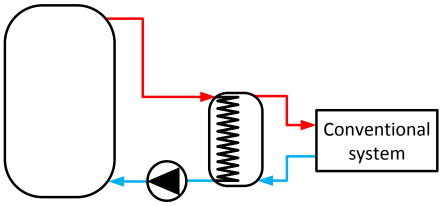
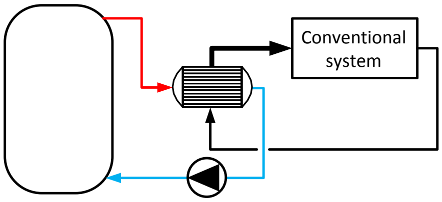
Table 6-3: Storage interconnection concepts

Description	Schematic concept
Single buffer storage • Recommended if possible • Low heat losses and piping effort • Temporal reduction of active storage volume possible, when concepts “mixed charging return flow” and “stratified process return flow” are combined (Table 6-2 and • Table 6-4)	
Parallel • Only for low ceilings • Exact hydraulic balance important for uniform flow • Maximum 2 storages parallel	
Description	Schematic concept
Serial • Only for low ceilings • Forced stratification • Possible destruction of exergy by heat entrainment	
Priority circuit • Seasonally adaptable active storage volume • Separate charge and discharge possible • Different processes can be supplied at different temperature levels	
Return flow **bypass** • Hot process return flow can be bypassed • Beneficial if process return flow is colder than bottom storage temperature • Collector loop can operate at process temperature	

6.2.4 Storage discharging

In some cases the components for discharging the solar buffer storage can be distinguished from the components for solar heat integration, and in some cases they are the same. The selection of an optimal discharging concept mainly depends on the integration concept with its integration flow and return temperature characteristics. Effective interaction between the charging and discharging concepts is of high relevance for optimal SHIP system gains. In case of multiple connected SHIP integration points, discharge to the connected load with the lowest temperature level should be prioritized.

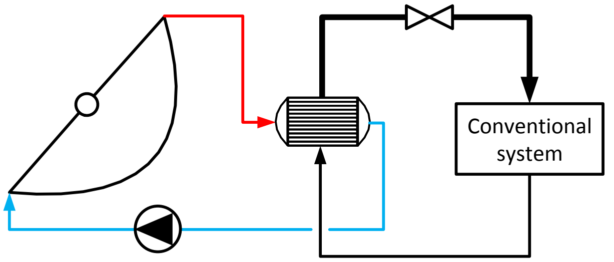
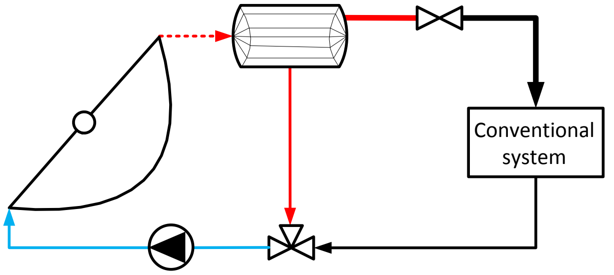
Table 6-4: Discharging strategies for solar heat integration

Description	Schematic concept
Direct • Storage medium is process medium • Storage is integration point	
Indirect with **stratified process return flow** (optional) • Process medium and storage medium can differ • Variable heights for discharge flow and return flow possible (stratification for high return flow temperatures indicated)	
Description	Schematic concept
Indirect with **fresh water station** (M = mixing valve) • Return flow addition limits integration flow temperature to a maximum or allows to deliver a set temperature • This temperature level is never exceeded	
Indirect with **pre-heating storage** • Suitable for batch processes with high peak demand of process medium • Discharge can also be realized by external heat exchanger	
Indirect with via **evaporator** • For high-temperature storages only • Evaporator is integration point	

6.2.5 Solar steam generation

Solar steam generation systems differ significantly from low-temperature SHIP systems. For this purpose, concentrating collectors without storage are applied. In Table 6-5 a system for indirect steam generation and a system for direct steam generation are introduced.

Table 6-5: Solar steam generation concepts

Description	System scheme
Indirect steam generation • For collectors with liquid heat carrier • No storage needed • Three way valve is integration point	
Direct steam generation • For steam generating collectors • No storage needed • Three way valve is integration point	

6.3 Exemplary System Concepts

In this section, seven exemplary SHIP system concepts are given. They cover a wide range of industrial and commercial applications on process and supply level for liquid and gaseous (steam and air) media. In reality, the necessity of storage as well as its charging and discharging strategies will vary between different applications and load profiles. However, each integration concept described in Chapter 5 can be allocated to one or more of these seven principle system concepts. For simplification, the following schemes only show a very basic set of system components. The focus is on the integration concept itself.

6.3.1 Heating of a fluid stream via heat exchanger

Indirect SHIP integration is solar heat transfer via a heat exchanger, while in the case of direct integration the media within the solar buffer storage (or the collector) are identical to the process medium or HTF and not hydraulically separated. Figure 6-3 shows a SHIP system concept for indirect heating of fluid streams. The return flow from the conventional system is solar pre-heated before it enters the conventional boiler. A non-tracked collector generates solar heat. The external heat exchanger allows running the collector circuit and the storage charging loop using different heat transfer media, but requires an additional pump in the system. The discharge concept is a so called “fresh water station” that is well suited to supply a certain integration flow set temperature. The system is pre-heating until the storage top temperature exceeds the maximum integration flow temperature. If the current charging power to the storage remains higher than the discharging power, the mixing valve limits the integration flow temperature to the maximum by return flow addition. In this operation mode, the conventional heater can be switched off.

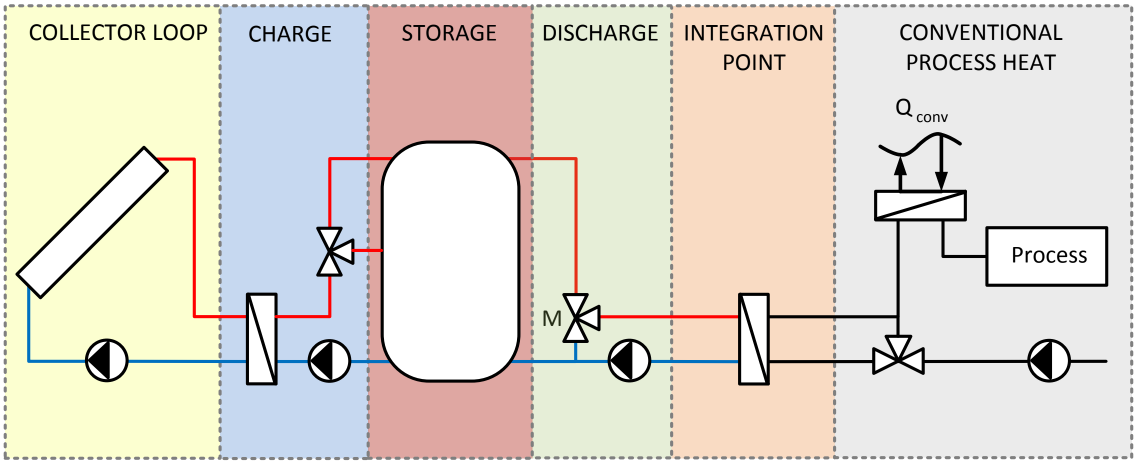


Figure 6-3: Heating of a fluid stream via heat exchanger. Very common concept to supply certain integration flow set temperatures or to limit the integration flow temperature to a maximum (M = mixing valve, other = switching valves)

6.3.2 Heating of a fluid stream via pre-heating storage

Figure 6-4 shows a system for storage discharge by charging a smaller, so called "pre-heating" storage that integrates solar heat into the conventional system (integration point). This set up is suitable for short and high peak load demands (i.e., high mass flows as for cleaning applications). The (intermediate) process medium is ideally heated to the integration set temperate within the pre-heating storage. An example for such a discharging strategy is the heating of water for washing machines. These machines are quickly filled and conventionally heated by steam injection.

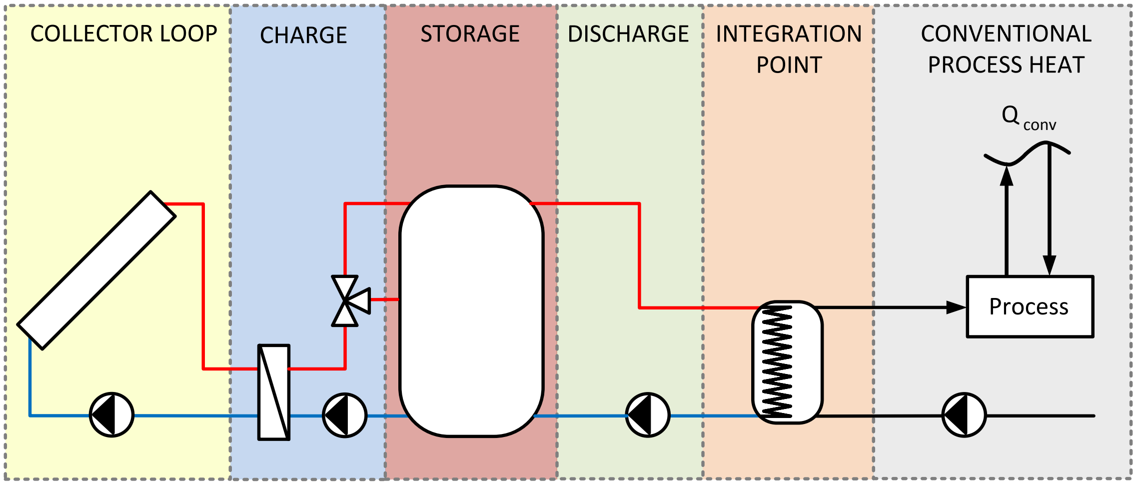


Figure 6-4: Heating of a fluid stream via pre-heating storage, which is a suitable concept for high mass flows in short time (e.g. washing/cleaning) and for integration in parallel to the conventional supply.

6.3.3 Heating of process bath or vessel

Figure 6-5 shows a system designed to maintain temperatures in baths or vessels. This system aims to provide a constant integration set flow temperature. In this case, the buffer storage is discharged by an internal heat exchanger that is immerged into a bath or a vessel (integration point). In the morning, the mixed charging return flow ensures that the collector loop quickly supplies the integration set temperature without charging the storage. When also the integration return flow is stratified (directed to the top of the storage), then the storage almost acts as a hydraulic separator, since only the top of it is actually flown through horizontally. At times with no load (e.g. at weekends), the storage can be charged as usually and later discharged by feeding the integration return flow to the bottom of the storage. This way, minimal heat losses of the system and high utilization ratios can be achieved.

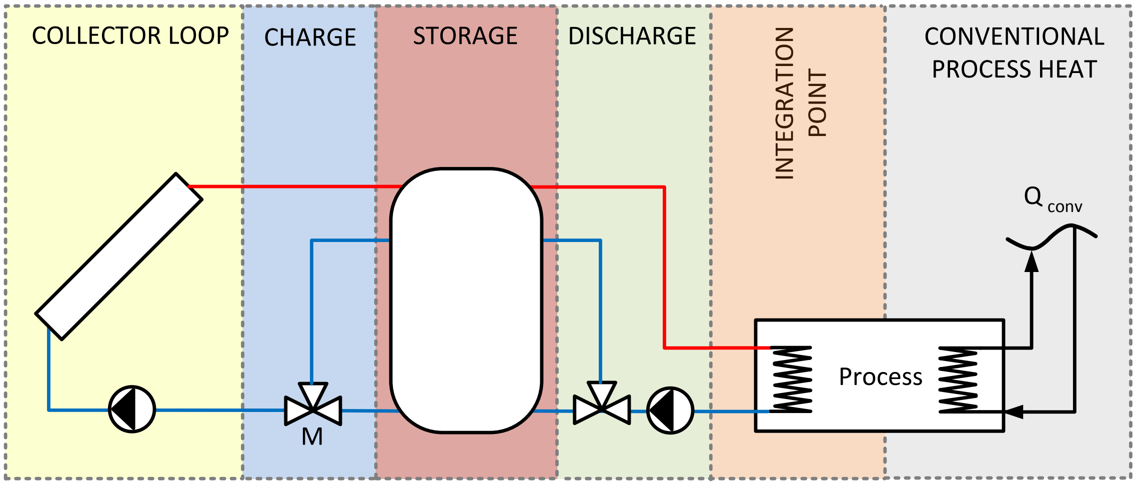


Figure 6-5: Heating of a bath or vessel. With mixed charging return flow and stratified process return flow the storage behaves like a hydraulic compensator if it is not needed (M = mixing valve, other = switching valve).

6.3.4 Direct heating network integration

In Figure 6-6, a direct integration of solar heat into a pressurized hot water supply network is shown. Here a stationary collector pre-heats the return flow of the network (return flow boost). The hydraulic compensator balances possible pressure difference between the two pumps caused by, for example, different flow rates. Alternatively, the boiler can also be installed in parallel to the solar loop. This system concept is effective for low solar fractions and constant heat demand where no storage is needed.

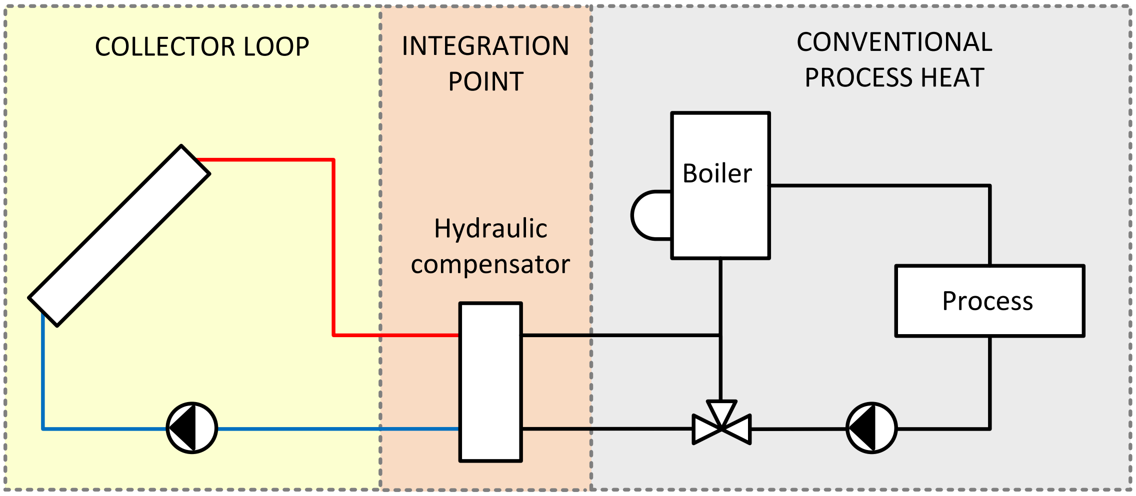


Figure 6-6: Heating network supply via return flow boost

6.3.5 Direct pre-heating of air

Figure 6-7 gives an example for an air-based system. The air is heated or pre-heated directly within an air collector. Adding ambient air can control its outlet temperature. The integration flow temperature of the air is serially heated further if needed. This collector loop concept is suitable for convection air dryers or for pre-heating of combustion air.

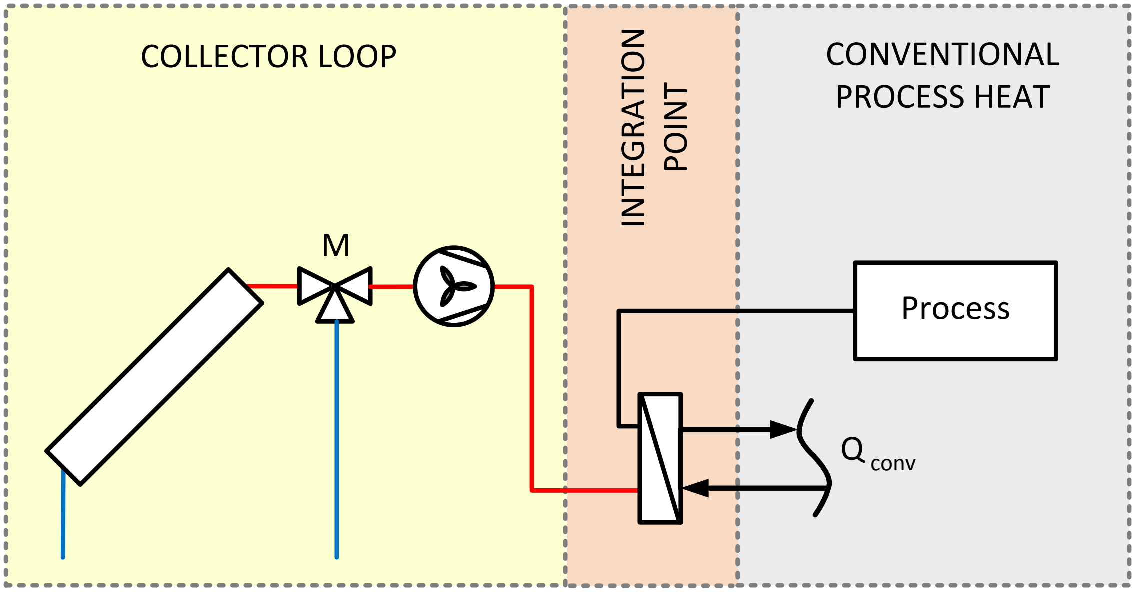


Figure 6-7: Pre-heating of air for drying

6.3.6 Indirect solar steam generation

Figure 6-8 shows a system set up for indirect steam generation. For steam generation, tracking concentrating collector types are usually employed. For indirect steam generation, the medium (thermal oil or pressurized water) is heated in the collector field and transfers its heat to the water feed in the evaporator. The medium evaporates in a kettle type boiler and is then injected into the conventional steam network via a valve (the integration point).

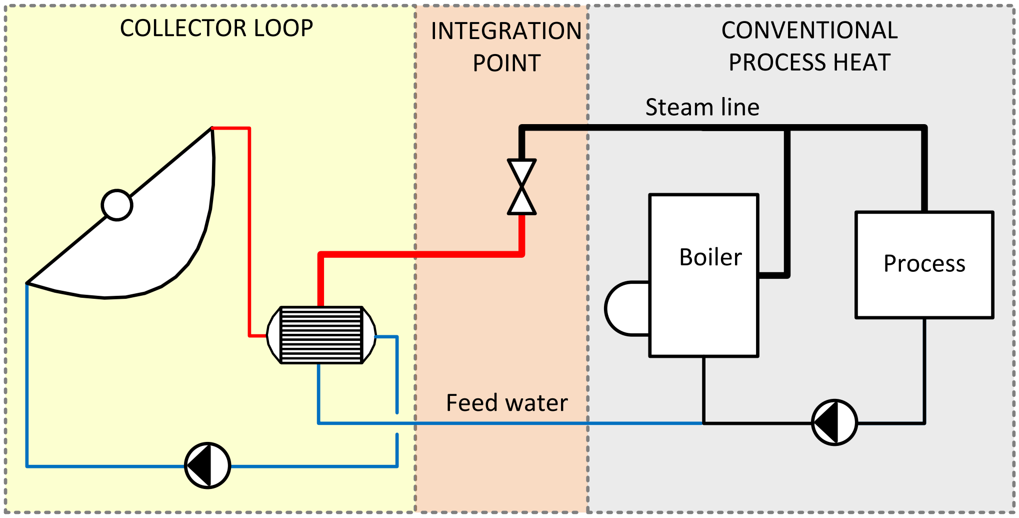


Figure 6-8: Indirect steam generation

6.3.7 Direct solar steam generation

In Figure 6-9, a system set up for direct steam generation is shown. In this case, the medium evaporates directly inside the absorber tubes. The two-phase flow at the collector outlet is filled into a steam drum. This drum is the water feed tank for re-circulation and for separating the two-phase flow into condensate (which is re-circulated) and saturated steam, which is integrated into the conventional steam network via a valve (integration point) when the temperature and pressure are sufficient. This type of system works best at a low solar fraction. Steam storages for such systems are not common because of their high costs.

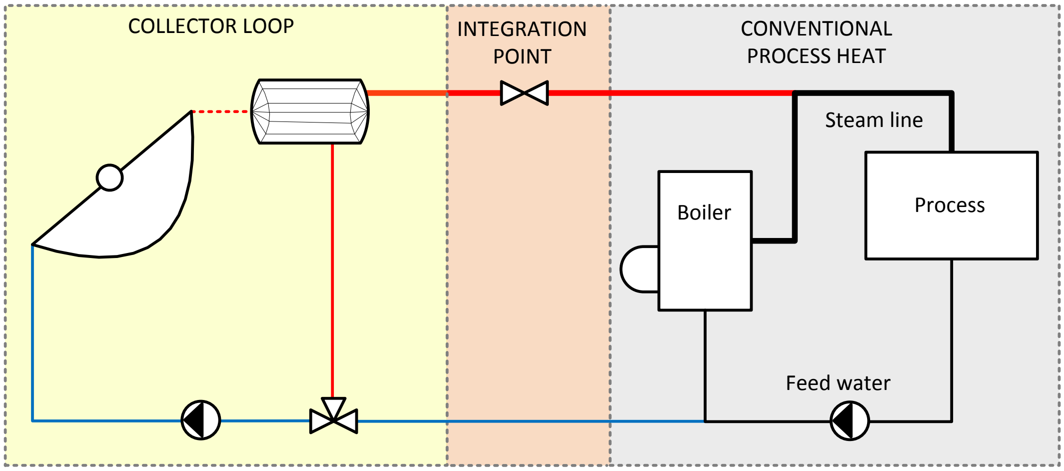


Figure 6-9: Direct solar steam generation

6.4 Selection of a Solar Heating Concept

Table 6-6 links the SHIP integration concepts given in Chapter 5 to the exemplary SHIP system concepts described in section 6.3 to give planners a quick idea of the SHIP system concept(s) appropriate for a considered integration concept. The abbreviations used for the SHIP integration concepts are explained in Table 5-1.

In order to simplify the SHIP system selection, Table 6-6 does not differentiate between the fluid streams “process medium” and “input stream” because the type of integration is similar and does not have a major impact on the SHIP system design. The SHIP system is characterized instead by the type of heat exchanger used at the integration point and the heat transfer medium. Therefore, air was added as a heat transfer medium and “no heat exchanger” discharge is possible for direct solar heating. In addition, different media are summarized.

Table 6-6 shows that solar heating of a fluid stream via external heat exchanger is the most applicable design. This is due to the fact that an external heat exchanger can transmit solar heat into various places on both supply and process levels, and in parallel or serial. The basic system components therefore are similar for different options. The dimensions and the actual operational strategies, such as charging and discharging of the storage, must be matched to the real load profiles of the specific integration points supplied. Industrial load profiles can vary a lot in terms of mass flow, temperatures and operation times.

Even if two different industrial plants have integration points in the same place this does not mean that the same storage size and charging structure are suitable in both cases.

Table 6-6: Table linking the SHIP integration concepts of section 5.2 to the exemplary SHIP system concepts described in the previous section 6.3. The abbreviations used are explained in explained in Table 5-1. The first letter couple defines the integration level (supply level or process level), the second letter describes the conventional heat transfer system and the last letter couple determines (in combination with the second letter) the actual heat transfer fluid at the integration point. The integration concept "N" is for direct solar heat integration without heat exchanger.

				Non-steam applications					**Steam applications**	
Solar heating system concept				Indirect heating of fluid stream via external heat exchanger	Indirect heating of fluid stream via pre-heating storage	Indirect heating of bath / vessel via internal heat exchanger	Direct heating network integration in parallel or via return-flow boost	Direct heating of air (open system)	Indirect steam generation	Direct steam generation
Supply Level	Steam network	Steam generation	SL_S_PD							X
			SL_S_PI						X	
		Boiler feed water	SL_S_FW	X			(X)			
		Make-up water	SL_S_MW	X	X					
	Liquid heat transfer Media	Parallel integration	SL_L_PD				X			
			SL_L_PI	X						
		Return flow increase	SL_L_RF	X			X			
		Storage or cascade	SL_L_SC	X	(X)	X				
Process Level		PL_E_PM PL_E_IC PL_E_IS PL_S_V PL_E_HB	E	X	(X)		(X)			
		PL_I PL_S_LP	I			X			(X)	
			N				X	X		

7 Identification of Suitable Integration Points

Ilyes Ben Hassine

Highlights Chapter 7:

- Generally solar heat can be integrated at different points in an industrial plant
- The most suitable integration points can be identified based on a set of **indicators**
- Each heat sink has indicators of suitability for solar assistance, called **pre-integration indicators**
- Each solar heat integration concept of the appropriate sink can be assessed by means of **post-integration indicators**
- A methodology for fast ranking of different integration points is proposed as a basis before the decision

Once process optimization and energy efficiency measures are implemented within an industrial plant, the planner of a SHIP system is generally confronted with several unit operations or heat sinks that can be assisted with solar heat. Before starting the techno-economic analysis of all integration possibilities (as indicated in step 7 of the assessment methodology), it is useful to filter them and identify the most promising ones. This chapter introduces a two-step method to rank different integration points by analyzing their suitability for solar heat supply. A matrix is proposed as a ranking tool, where in different technical criteria are discussed regarding their relevance. Limits of the method are mentioned in the last chapter.

7.1 Introduction

To decide where an existing industrial plant should be assisted with solar heat, many aspects have to be taken into account. While the main differences of process and supply level integration may be summarized within a few aspects (see Table 7-1), the correct choice of the most suitable integration point is a complex task. The term ‘point’ is used instead of unit operation or sink to highlight the fact that some sinks could be assisted at different levels (e.g., heat exchangers) and temperatures.

Table 7-1: Basic aspects of solar process heat integration on process and supply level

Criteria	Process level	Supply level
Detailed process data	Required (at least for target processes)	Not needed (rough data may suffice)
Preliminary **process integration** analysis	Essential for appropriate solar system design	Generally recommended, yet sometimes superfluous
Flexibility to adapt to later changes in processes	Low	High
Collector efficiency	Potentially higher (due to lower operating T)	Usually lower (except for heating of boiler makeup-water

Solar heat contribution potential	Restricted (to share of the supported process(es) on the overall heat demand)	Usually higher (since all connected processes are supplied indirectly)
Heat storage necessity	Depends on the profile of the selected process stream(s) with respect to solar availability, and sizing of solar contribution	Not necessary if not exceeding the base load of the utility

The method presented in this chapter includes two steps. The first step, also called the pre-integration step, mainly focuses on the sink's heat consumption before the solar thermal system is integrated. By means of general suitability indicators, heat sink candidates can be identified. The second step takes into account the possible integration scheme/concept adopted for each of the candidates and applies technical criteria for ranking them. A matrix using the suitability indicators and integration criteria is then presented as a ranking tool.

The indicators and criteria described below were collected from different case studies and are generally independent of the industrial sector. Planners should take them into account to ensure an objective and thorough assessment of all integration possibilities. Due to the large number of suitability indicators, it is suggested to use the ranking matrix as a tool to facilitate the evaluation of different integration schemes. Of course, other tools, such as cost-benefit analysis may be applied. The proposed ranking method should be seen as a filtering tool to identify the most suitable integration candidates, and will enhance the planning process by reducing the number of relevant integration points. A more detailed techno-economic evaluation of the candidates is presented in the Assessment Methodology (Chapter 3) within "Analysis of Integration Points" (step 7).

The data collected in the process integration step (Chapter 4) provides a good basis for the method introduced. Technical information on the unit operations, heat supply, and distribution network as well as the operational schedules and the required temperatures are used to identify suitable integration points within the industrial plant. The identification method is also based on details such as the size of existing heat exchangers or the operation strategy that should be prepared for process integration.

7.2 Evaluation of Heat Sinks and Integration Concepts

The first evaluation step is based on a set of indicators evaluated according to heat demand figures. The availability of these data for all considered unit operations (from the analysis of status quo) is crucial for a good quality of evaluation. The second evaluation step is based on a set of post-integration criteria evaluated for different integration schemes.

The indicators for the first step are grouped into three sections: demand, schedule, and technology. For each section, the indicators are listed in Table 7-2 according to their impact on future solar integration (the indicator in the first row is more significant than the one below etc.).

The suitability indicators have been chosen based on a set of considerations related to energy consumption and operation characteristic. Every indicator can be quantified through a variable. The suitability range of each variable will not be limited in this document; however general rules can be applied to evaluate them as described in the following paragraphs.

Table 7-2 List of suitability indicators of heat sinks

		Indicator name	**Indicator variable**	**[unit]**
pre- integration	**Demand**	process (return) temperature	T_p	[°C]
		tempearture lift	ΔT	[°C]
		annual heat demand	Q_a	[kWh/year]
		storage capacity	Q_{st}	[kWh]
		storage charging	$\dot{Q}_{st}$	[kW]
		operation time	t_{op}	[h/year]
		mean load	$P_{av} = Q_a/t_{op}$	[kW]
		recirculation	$1/rec$	[-]
	Schedule	daily demand coincidence	$C_d = Q_{mid}/Q_{day}$	[%]
		demand seasonality	$C_a = Q_{sum}/Q_a$	[%]
		demand uniformity	$unif = P_{av,day}/P_{max,day}$	[%]
		rescheduling	t_i	[h]
	Technology	equipment supply quality	$\pm\Delta T_e$	[°C]
		product supply quality	$\pm\Delta T_p$	[°C]

The first two indicators T_p and ΔT are related to the temperature level on the process side. The choice of the collector type, the collector efficiency and the estimated solar gains usually depend on this level. ΔT is the temperature lift on the process side and it theoretically gives the margin, within which the sink may be assisted.

The process temperature describes the typical temperature of the process medium during operation. As described in chapter 6 (see Figure 6-1) the most relevant temperature for the efficiency of solar pre-heating systems is the integration return temperature. On the process side, this is most closely linked to the process return temperature, which is the temperature on the process side that can be increased via the solar thermal system. The **process return temperature** is therefore the appropriate indicator for solar preheating systems. It clearly differs from the process temperature: In a process where a product is heated from 20°C to 90°C, the process temperature is 90°C, whereas the process return temperature can even approach 20°C. Taking solar gains and the collector efficiency into account, sinks with low T_p and large ΔT are more suitable for solar supply than those starting from a higher return temperature and allowing a narrow temperature lift. The rule generally applies for sinks where the process medium or an input stream can be preheated (e.g. PL_E_PM in Figure 5-11).

For sinks where the solar heat exchanger is foreseen to be in parallel to the conventional heating system (e.g. PL_I in Figure 5-15), a set point for the integration flow temperature is matched and ΔT is not easy to determine. In this case, the **process temperature** itself (e.g. the bath temperature to be maintained) is the main criterion. Here again: the lower the temperature, the better are the conditions for solar thermal assistance.

The annual heat demand Q_a is one of the main criteria to be considered before integrating solar energy. It strongly determines the solar yield that can be achieved for the corresponding sink. This indicator has to be evaluated in a comparison between all sinks within the production site. A milk drying process with a high demand share (e.g. 1/3 of the annual consumption in a dairy plant) is more interesting than the space heating system of the reception office.

The available storage Q_{str} and charging $\dot{Q}_{str}$ capacity indicate how flexible the operation is in regards to fluctuating supply and demand profiles. Generally, large capacities facilitate the integration of supplementary heat sources. Short-term (diurnal) to medium-term (weekly) storages can be seen as of high potential while sinks without own heat accumulators are of lower significance.

The operation time t_{op} accounts for the annual number of hours during which the operation is running. Especially for tropical climate zones the longer the process time, the higher the potential for solar integration. Depending on the industrial segment, the range of high suitability differs. For example in building material industry most of the operations meet the criteria of moderate to high operation times (about 4000h/year), so these values are considered as indicative of a moderate suitability. In the building material industry operation times above 6000 h correspond to high potential and for those operations with less than 3000 h is considered low potential.

The mean load P_{av} is very useful for pre-dimensioning of the solar heat exchanger and storage tank. High mean capacities along with constant loads allow large solar installations with low specific costs and generally make the sink more attractive for solar integration; however the potential of system capacity has to be seen within the climatic and spatial boundary conditions of the plant. If, for example, the available surface for collector installation allows an aperture of only 100 m², large sink loads over 500kW can be appropriate sinks for solar heat supply, as well as moderate loads of 100 kW.

The recirculation ratio rec provides an indication if the unit operation is running in an open, a closed or semi-closed mode. Since open operations without mass or heat recovery generally have low process temperatures, they are very suitable for solar heat integration. The opposite is true for a high recirculation ratio, leading to a lower potential for solar integration.

The coincidence of solar radiation with heat demand is the most important indicator in the schedule section. Especially for sinks with low storage capacities and loads, the achievable solar gains can strongly depend on this indicator. The coincidence is evaluated on a yearly basis through the thermal demand seasonality C_a, which characterizes the ratio of the summer (heat demanded from April to September for sites in the northern hemisphere) to the annual consumption. A daily evaluation C_d may also be useful for sinks with low seasonal dependency. In this case, C_d is calculated as the ratio of the average thermal demand between 11 AM and 3 PM to the daily one. Once both indicators are calculated, heat sinks with values above 0.6 have to be grouped as most interesting ones where coincidences below 0.3 show low suitability for solar feed-in.

The thermal demand uniformity $unif$ characterizes the ratio between average and peak load during one operation cycle. A low uniformity below 0.3 indicates the need for additional heat utilities (e.g. the main boiler) to handle high peak loads. A high uniformity over 0.7 makes the solar plant much easier to design for planners. Sinks with higher uniformities $unif$ have to be privileged in the evaluation.

If rescheduling of a unit operation is allowed and technically feasible, its coincidence potential can be enhanced adequately, and better conditions for solar integration can therefore be obtained. The indicator suitability is measured by evaluating the operation interval t_i that can be shifted to the time between 11 AM and 3 PM. If many sinks can be rescheduled, the highest suitability factor will be assigned to the sink with the lowest impact on the whole production time plan.

The last two indicators describe the requirements of the process equipment and of the product based on their sensitivity to temperature or pressure fluctuations in the supply line. Especially in solar heating systems with limited buffer volumes and on/off control of the charging loop pump, temperature peaks are common. Solar steam generation systems are also often run in partial load due to the fluctuating radiation. This generally leads to pressure oscillations in the supply line and may reduce the equipment lifetime. The sink with the largest allowed fluctuation range ($\pm\Delta T$) has therefore the highest potential for solar heat integration. Both indicators are of the same significance for solar heat integration.

Once the heat sinks with higher suitability for solar feed-in are identified, the second evaluation step can be started in consideration of technical criteria/requirements. Here, the integration schemes are evaluated as a whole. The set of criteria defined in Table 7-3 is based on constraints that apply if solar thermal systems are integrated into the existing heat supply system. Some criteria are hydraulic or control specific, while others are generally related to the spatial location of the sink and to its existing supply utility. The impact of some criteria is explained in the paragraph below.

Table 7-3 List of criteria for integration concepts

Criteria	Description
Process continuity	No sink interruption needed during maintenance or repair of solar thermal system
Load balancing	Utilization of excessively operating supply utilities will be reduced
Control Hardware	No extension in supply equipment control hardware is required
Control Software	No changes in supply equipment software are required
Fouling risk	No fouling risk for the added HEX - if any
HX sizing	Existing heat exchanger can be used for solar feed-in
Storage sizing	Addition of storage capacity can be avoided
Distance to solar	The solar plant is close (< 50 m) to the supply line of the sink
Auxiliary energy	No significant pressure differential to be overcome, pumps within solar heating system are only needed for circulation
Estimated solar yield	High solar yield estimated
Multi-supply	Other heat sinks can be easily co-assisted
Modulation	The supplying or back-up heat utility can be modulated

Dependency on radiation	The estimated solar yield is slightly dependent on the direct fraction of solar radiation
Replacement of CHP	The utilization of (planned) CHP utility will not be reduced
Replacement of WH/HR	The use of waste heat (compressors) will not be unnecessary reduced

From an operational point of view, the supply reliability and safety are much more important than the solar gains that can be achieved in an industrial plant. Therefore, the first criterion that is to be considered when feeding-in solar energy is the production safety. An indication for a non-suitable integration scheme could be the need for production interruption during maintenance of the solar installation. A design of a solar thermal system without solar heat storage and backup is not the best choice in combination with a heat sink requiring high supply quality in terms of feed temperature and pressure stability. The intermittent solar radiation may lead to low solar gains or unnecessary process shutdowns.

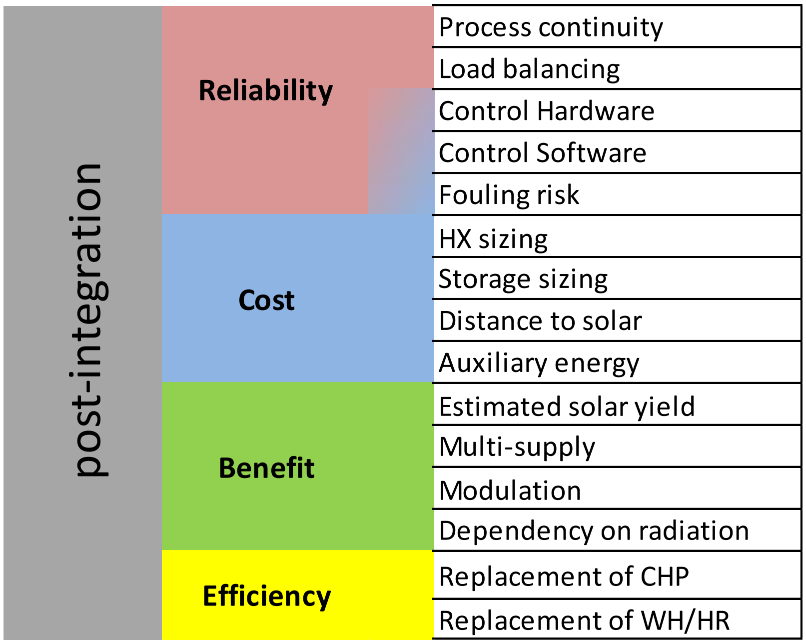
Heat exchangers and storages are important cost drivers in solar process heat installations. Therefore integration schemes allowing -if any- small sized components are favorable. Several changes in the control hard- and software of the main supply utility or of the process machinery itself may put the production continuity at risk and therefore have to be avoided. Heat recovery and CHP are competitive technologies that also have to be taken into account by the planner.

The criteria load balancing and modulation brings the interaction between the solar thermal system as heat source and the existing heat utility into play. In some cases an existing boiler is operated at nearly full capacity, so that solar integration at the appropriate supply level would balance heat loads and enhance the scheduling flexibility within the site. Also higher solar gains are expected if the back-up system can be modulated down to low capacities and if more heat sinks are technically easy to assist.

The dependency on radiation describes how the supply properties, temperature and pressure, are susceptible to fluctuations in solar radiation. Generally solar process heat systems with large buffers are able to cope with short-term fluctuations and provide constant supply properties. In contrast, the integration concept of direct solar steam generation (**SL_S_PD)** is not suitable for regions with low or particularly intermittent beam irradiation due to the discontinuity of supply. Therefore schemes with low dependency of the supply properties on the radiation course are advantageous.

For simplicity, the criteria of Table 7-3 are reorganized in four sections: reliability, cost, benefit and efficiency.

Table 7-4: The integration criteria sections



post-integration	**Reliability**	Process continuity
		Load balancing
		Control Hardware
		Control Software
		Fouling risk
	Cost	HX sizing
		Storage sizing
		Distance to solar
		Auxiliary energy
	Benefit	Estimated solar yield
		Multi-supply
		Modulation
		Dependency on radiation
	Efficiency	Replacement of CHP
		Replacement of WH/HR

7.3 Ranking of Integration Points

The ranking matrix shown in

Figure 7-1 is developed to help planners in the choice of the most appropriate integration point(s) by assigning colors with respect to the considered indicator and criteria sections from last chapter. The evaluation is applied to each column of the matrix (sink) separately. A common color is assigned to the sections (demand, schedule, technology, reliability, cost, benefit and efficiency) instead of to the each indicator to reduce the complexity of the matrix. The meaning of the three colors red, yellow and green is as follows:

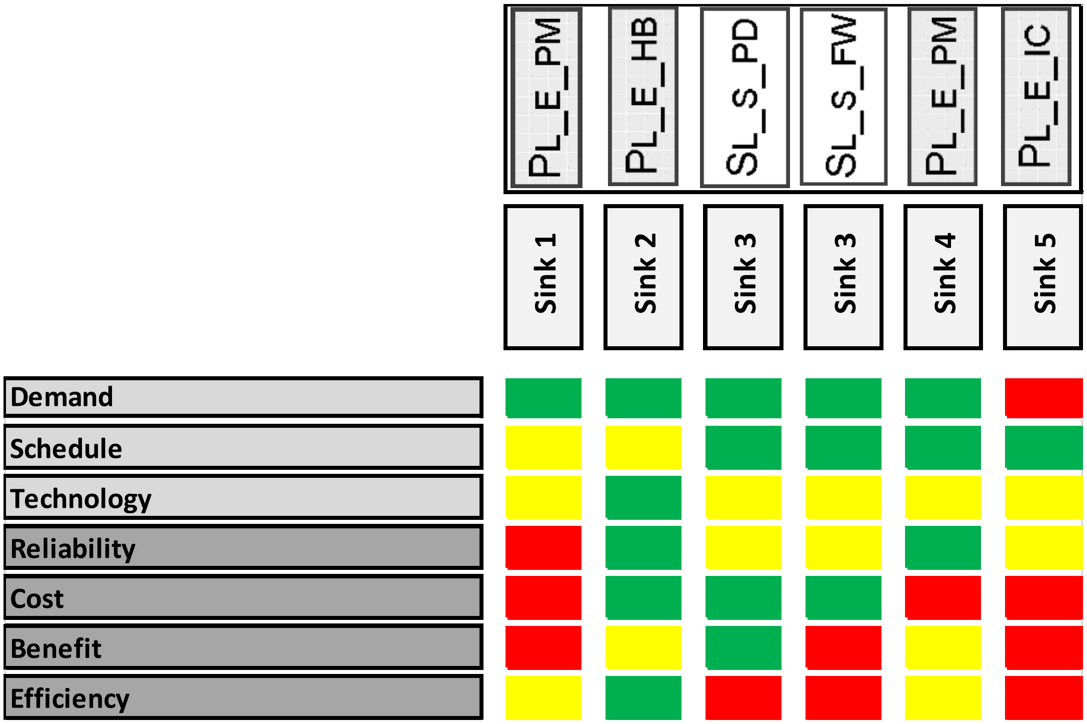
Table 7-5: Meaning of colors for pre- and post-integration

	The sink has an indicator for	**For the integration concept, the criterion**
🟩	high suitability	Can be easily fulfilled
🟨	Moderate Suitability	Cannot be fully fulfilled, however low Efforts/costs are expected
🟥	low suitability	Cannot be fulfilled

To illustrate the assignment of colors, a ranking matrix for five different heat sinks of a meat factory is shown in

Figure 7-1 (sink 1 is a drying operation, sink 2 is a cleaning operation, sink 4 and 5 are both cooking operations and sink 3 is the steam supply network itself). Depending on the integration concept applied, two different candidates (direct steam generation and heating of boiler feed water) are derived from the same sink 3. Each column corresponds to one integration scheme per heat sink with the appropriate symbol from the classification chapter. Colors are assigned to the seven predefined sections. Intuitively, the column having the highest number of green 'boxes,' is the most appropriate integration point.

The ranking matrix clarifies that the cleaning operation (sink 2) has the highest potential for solar heat integration. Heating the boiler feed-water also represents a good candidate to be further considered. A detailed evaluation of the meat factory with colors assigned for each indicator and criteria can be found in the appendix (section 0).



	PL_E_PM	PL_E_HB	SL_S_PD	SL_S_FW	PL_E_PM	PL_E_IC
	Sink 1	Sink 2	Sink 3	Sink 3	Sink 4	Sink 5
Demand	🟩	🟩	🟩	🟩	🟩	🟥
Schedule	🟨	🟨	🟩	🟩	🟩	🟩
Technology	🟨	🟩	🟨	🟨	🟨	🟨
Reliability	🟥	🟩	🟨	🟨	🟩	🟨
Cost	🟥	🟩	🟩	🟩	🟥	🟥
Benefit	🟥	🟨	🟩	🟥	🟨	🟥
Efficiency	🟨	🟩	🟥	🟥	🟨	🟥

Figure 7-1: The ranking matrix (exemplary for solar heat integration into a meat factory)

Ideally the choice of the color for each element of the matrix should be based on previous knowledge of the studied processes or of comparable sites. Limits of this ranking method are discussed in the next chapter.

7.4 Comments

The order of criteria shown in Table 7-2 and Table 7-3 does not apply in each site and can be redefined by the planner: for example load balancing may be the most important argument (criterion) to integrate solar energy into an industrial plant. The decision how to fill the ranking matrix can often be a matter of feeling, especially if the project is still in the first stages. In many cases the costs of or effort needed to integrate one point is difficult to estimate or compare with other alternatives. Specific cost figures and nomograms like those used in Heß and Oliva (2010) are very useful in these cases.

Using efficiency curves and/or nomograms, the solar yield can be estimated on the basis of the operational temperature, heat demand and storage capacity. Detailed simulations can obtain more accurate results provided that the hydraulic layout and the control strategy are known.

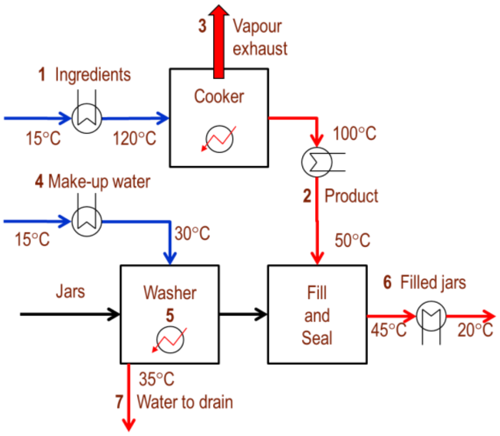
In many cases other non-technical criteria are decisive on where to integrate solar heat. A specific product line can be favorably assisted for marketing reasons. The collector field placement, which is mostly based on architectural aspects, can make solar integration economically more interesting for some sinks than for others.

Appendix

Appendix A

Example of Process Integration with Evaluation of Solar Process Heating

The methodology of Pinch Analysis is exemplified in the following by means of a simple process derived from VDI (2006), whose flowsheet is represented in Figure 0-1. The process consists of a food packaging line, in which ingredients are heated, cooked, and filled into jars. The jars are previously washed in a washer. The product is concentrated by evaporation during a cooking process. The available utilities are steam and cooling water respectively.



#	Name	T_{in} [°C]	T_{out} [°C]	Flow [kg/s]	c_p [kJ/kg^{-1}K^{-1}]	Heat rate [kW]
1	Ingredients heating	15	120	4.0	3.0	1260
2	Product cooling	100	50	3.6	2.8	500
3	Vapor condensation	80	79	0.4	1000	400
4	Washer make-up water	15	30	1.8	4.18	112.9
5	Washer lye bath holding	80	84	17.9	4.18	300
6	Filled jars cooling	45	20	6.0	2.0	300
7	Washer water to drain	35	20	1.5	4.2	94

Figure 0-1: Process flowsheet (left) and corresponding list of process heat sources and heat sinks (right) of the food packaging line example process

The list of process heat sources and heat sinks of the food packaging line is presented in Figure 0-1 (right). It is assumed that the cooker cannot be modified at affordable costs for heat integration, so that it shall still be supplied by steam anyhow and hence is not to be included in the list of heat sinks for analyzing the heat recovery. At present, the cooker achieves both heating and cooking.

The cooling of the product, achieved at present by cooling water, can be called into question as well. The washer is a complex system including several baths and internal water flows at different temperatures which shall not be modified, except the heating of the lye bath to maintain it at 80 °C, presently heated by an immersed steam supplied heat exchanger. Considering the inlet temperature of ingredients and washer make-up water of 15 °C, the washer water flow to drain may be cooled if needed down to around 20 °C.

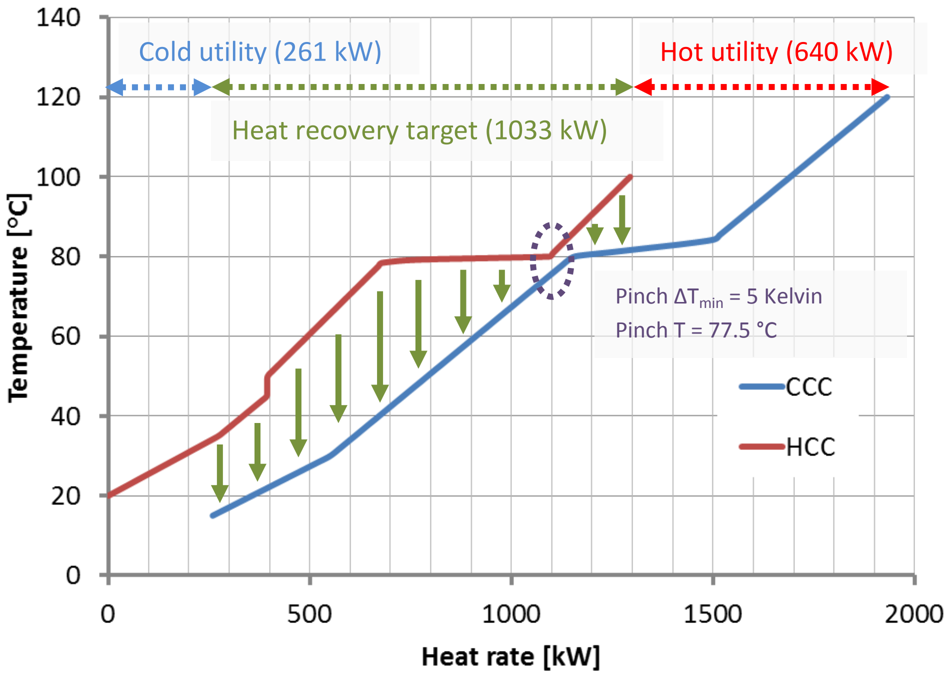


Figure 0-2: Hot and cold composites curves (HCC and CCC) at ΔT_{min} =5°C of the food packaging line example process

In Figure 0-2 the composite curves of the packaging process is shown. On the cold CC, the majority of the required heat rate from 80 °C to 84 °C corresponds to the heating of the washer lye bath (300 kW), while on the hot CC, the plateau at 80 °C stems from vapor condensation. As can be seen on the CCs graph, the heat recovery target is 1033 kW (highlighted with green arrows); the minimum hot (red arrow) and cold (blue arrow) utility consumptions are 640 kW and 261 kW respectively (the latter is actually not required since it stems from waste heat streams which can be released to the ambience without being cooled). The Pinch temperature lies at 77.5 °C (i.e. 80 °C for hot CC, 75 °C for cold CC).

Considering the shape of CCs, the heat recovery could be increased if the temperature of the lye batch would be decreased by at least 5 K (e.g. by optimizing the detergent, etc.) or the condensation temperature of exhaust vapor be increased (e.g. by avoiding unnecessary pressure losses at the exhaust, or cooking under a slightly higher pressure, provided it has no detrimental effect on the product quality), or a combination of these modifications. The feasibility of these changes should be checked in first priority, since process modifications can be very cost-effective and would change the process to be integrated correspondingly.

Another way to demonstrate the heat demand of processes in a system is the grand composite curve (GCC). The construction of the GCC bases on the hot and cold CC and is shown in Figure 0-3.

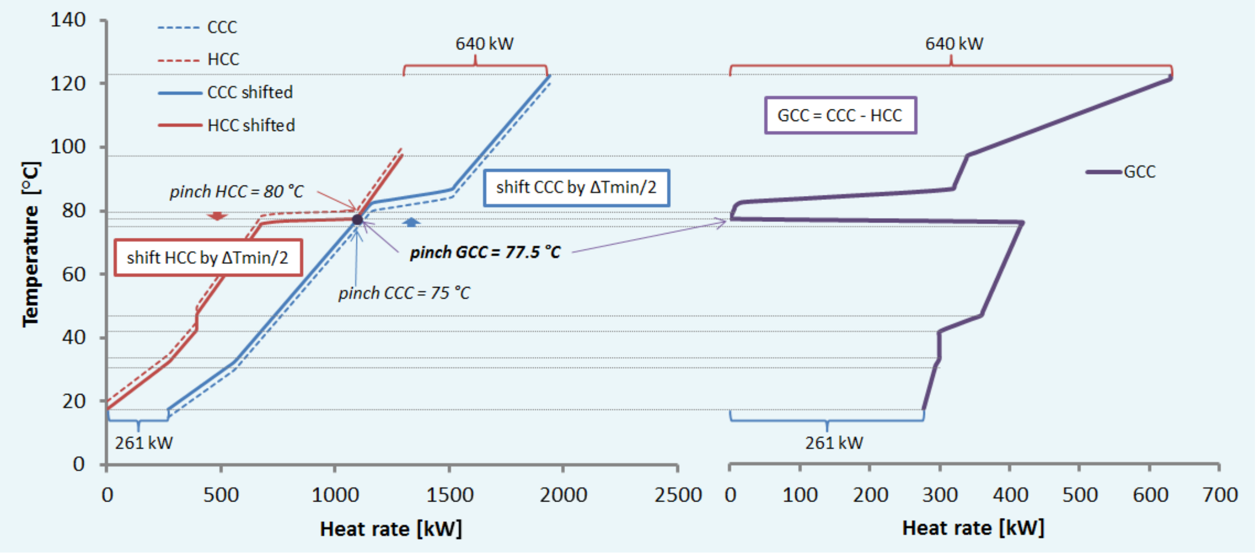


Figure 0-3: Construction of the grand composite curve (GCC) based on the hot and cold composite curves (CC).

The GCC is constructed based on the two CCs. First, the two CCs must be shifted so they touch each other at the Pinch point. In the example shown in Figure 0-3 the Pinch temperature is 77.5 °C and the ΔT_{min} is 5 K. The original hot CC (dotted red line) must be shifted *down* along the y-axis (temperature-axis) by $\Delta T_{min}/2$ (2.5 K) and the original cold CC (dotted blue line) must be shifted *up* by the same value. They meet at the Pinch temperature of 77.5 °C. This is the point where the GCC on the right touches the y-axis. Starting from this point the horizontal (heat rate) difference between CCC and HCC is drawn in the GCC graph. On each relevant temperature level (whenever the slope of either HCC or CCC changes) the heat rate difference of CCC and HCC is calculated and added in the GCC.

Already identified in the CCs, minimal demand on hot and cold utilities can also be seen in the GCC. 640 kW of hot utility and 261 kW of cold utility are required. Figure 0-4 shows in more detail the advantage of the GCC. It allows the assigning of utilities on different temperature levels. In a conventional way this would mean different levels of steam pressure, but this opens the possibility of considering solar process heat in the GCC, which is described below in more detail.

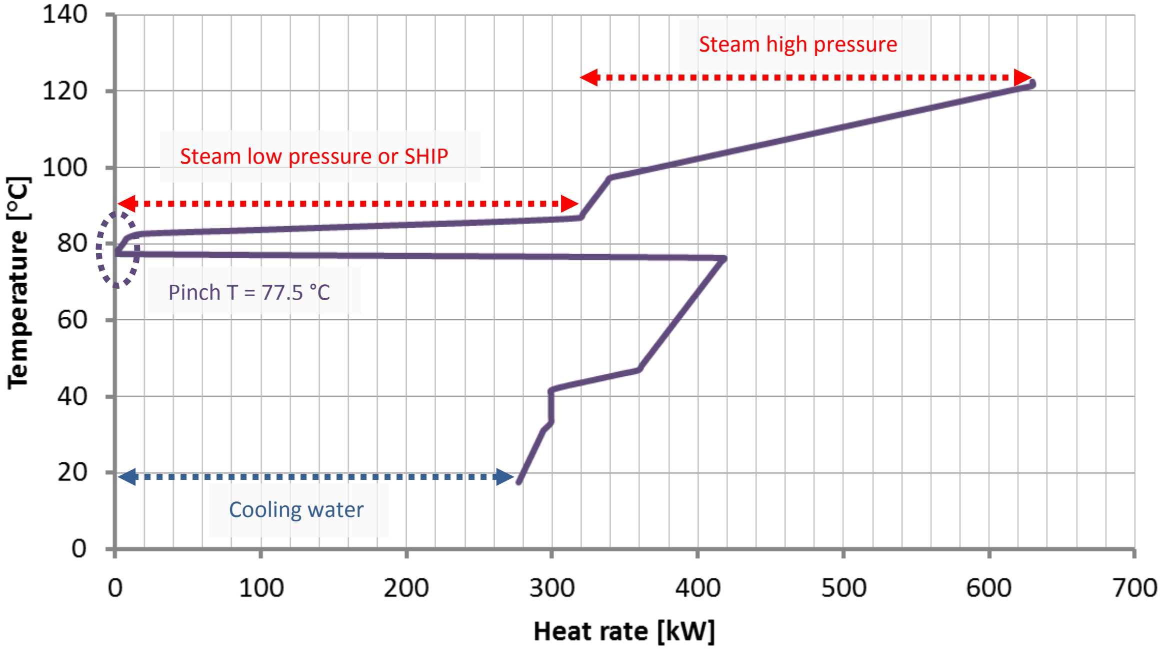


Figure 0-4: Grand composites curve (GCC) of the food packaging line example process

The GCC touches the vertical axis at the Pinch temperature, featuring a “nose,” immediately below this temperature. The large heat surplus stems from the condensation of cooking vapor, while immediately above, a large heat deficit appears mainly from the lye bath heating requirement. About 50 % of the hot utility requirement can be delivered at temperatures below 90 °C. Considering the shape and temperature level of the GCC, the engineer identifies at least three alternative ways to supply heat to the process to be compared (at least as regards the 320 kW of heat below 90 °C):

1) A compression heat pump (either by means of a closed cycle or open cycle resorting to mechanical vapor recompression), recovering heat from the heat surplus below the Pinch, and delivering heat above the Pinch to heat the lye bath;
2) A cogeneration unit based on an internal combustion engine;
3) Solar heat.

The Pinch Analysis based methodology aims at identifying the most promising options for solar integration, while ensuring that other cost effective alternatives aren’t overlooked. The possibilities to analyze solar heat integration based on the graphs are:

1. **Identification of minimum possible operating T and maximum heat rate of solar based on GCC**

For the integration of solar heat into processes, the process GCC (for integration on process level) as well as the utility GCC (for integration on supply level) are relevant.

A GCC represents a heat balance of several hot streams and several cold streams within temperature intervals, so heating and cooling requirements of several unit operations are included or even of several processes in total site analysis. Therefore several unit operations often compose the heat requirement per temperature level depicted in the curve.

If a solar plant is designed based on the GCC process then one assumes that it can supply several unit operations, some possibly only partially (e.g., reheating). In practice, this might be possible, but experience has shown that this is not always economical when the existing heat supply infrastructure must be changed. In addition, different supply and return temperatures (different temperature gradients for heat transfer) may be necessary and or possible for solar heat supply depending on the technical layout of the single unit operations. This has an important implication on the solar thermal system, as return temperatures influence the efficiency of the solar plant to a large extent. Therefore, the selection of 1-2 unit operations that can be best supplied by solar heat is often reasonable.

The utility GCC, on the other hand, shows the temperature levels at which the process heating and cooling requirements are actually supplied. Based on this curve, the analysis of solar integration on supply level is very possible. If one constrains themselves by the existing utility network then most likely the results will have higher exergy losses and less solar yield, depending on the location. But new possibilities may be considered, such as lowering the steam pressure.

As for all graphical curves in Pinch Analysis, there is a challenge to consider variable process streams (in terms of temperature and heat duty). Design considerations are therefore usually done based on time average representations (i.e., data averaged over time, considering time variable process streams as if they were continuous) or based on time slices (Thokozani, 2009).

For the food packaging line example process, the GCC represented in Figure 0-5 (left) highlights the possible placement of solar heat operated between 85 and 100 °C (the heat demand on this temperature range is around 340 kW). This heat demand is composed of heating the food ingredients prior to cooking and maintaining the temperature in the lye bath of the washer. However, as stated above, the curves as drawn assume full exploitation of the thermodynamic heat integration potential with all other streams. In the case when these heat recovery opportunities are not followed (heat recovery from filled jars requires an intermediate heat carrier and operators refrain from vapor condensation and wastewater due to fouling problems), the GCC can look very different, which highlights the importance to analyze the heat integration possibilities prior to designing the solar integration.

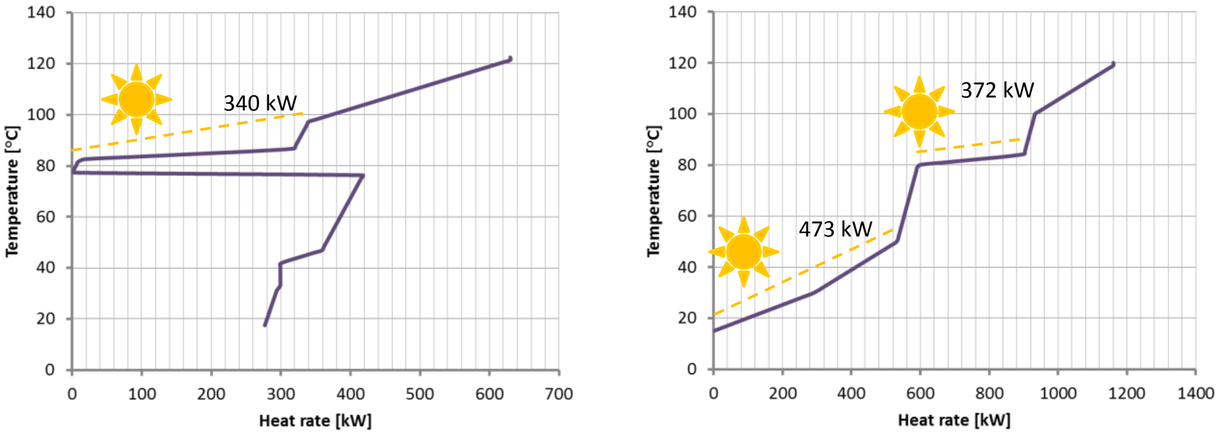


Figure 0-5: GCC of the food packaging line including all streams (left), and GCC excluding vapor condensation, washer wastewater, and filled jars cooling (right) at ΔT$_{min}$ = 5 °C. Note that the scales of the x-axis are different!

When no heat recovery can be realized, the GCC (Figure 0-5 on the right) features a heat sink starting as low as 15 °C (corresponding to 20 °C for heat supply) and any supply of solar heat above this temperature will be thermodynamically sensible. In Figure 0-5 the dotted lines represent several ways of theoretically integrating solar heat against the GCC to ensure adequate performances.

2. Drafting of the list of possible integration points of solar heat based on CCs

This makes sense for continuous processes, in particular, when the time variability only stems from solar heat, and/or when visual identification of suitable heat sinks to define the integration points is needed.

After the utilities (including solar heat) have been drafted based on the GCC, the hot utility streams can be added to the hot CC. For solar, the actual temperature and heat load will not be known until the integration point and the “solar process heat system concept” (the technical layout including all necessary components of the solar thermal system including storage, as well as the integration concept) are defined (this is because the efficiency varies according to the technical layout and to the supply and return temperatures, which will be optimized based on the integration point(s)). In spite of this limitation, the addition of a “solar stream” to the CCs provides the possibility to evaluate different integration points, at least for essentially continuous processes. To do this, cold process streams in the temperature range of the solar heat supply can be graphically highlighted and their corresponding heat rate calculated (this can be found from the list of heat sinks as well). This allows identifying promising candidate heat sinks while considering other practice relevant criteria.

However, since both hot CC and cold CC consist of several, partly superposed streams, design heuristics or computerized algorithms for placing heat exchangers have been developed (European Environment Agency, 2011) to turn these preliminary ideas based on the CCs into practical solutions. For solar process heat, such algorithms require the consideration of the time aspect (described in chapter 4.2.2). As described for the GCC, first design considerations will naturally be done based on time average representations. For solar heat, summer data should be applied to avoid a heat surplus in the summer time.

Figure 0-6 shows how the hot CC changes when adding the solar hot streams drafted on the GCC of Figure 0-5. This allows a different scenario of single or combination of heat sinks to be supplied with solar heat to be defined. It can be seen that the drafted heat rate corresponds to the maximum solar heat contribution that can be supplied for the selected temperature range. If the heat rate will be increased beyond these values then the cold CC should be moved to the right to maintain the ΔT_{min} at the economic optimum, hence increasing the hot and cold utility consumptions correspondingly.

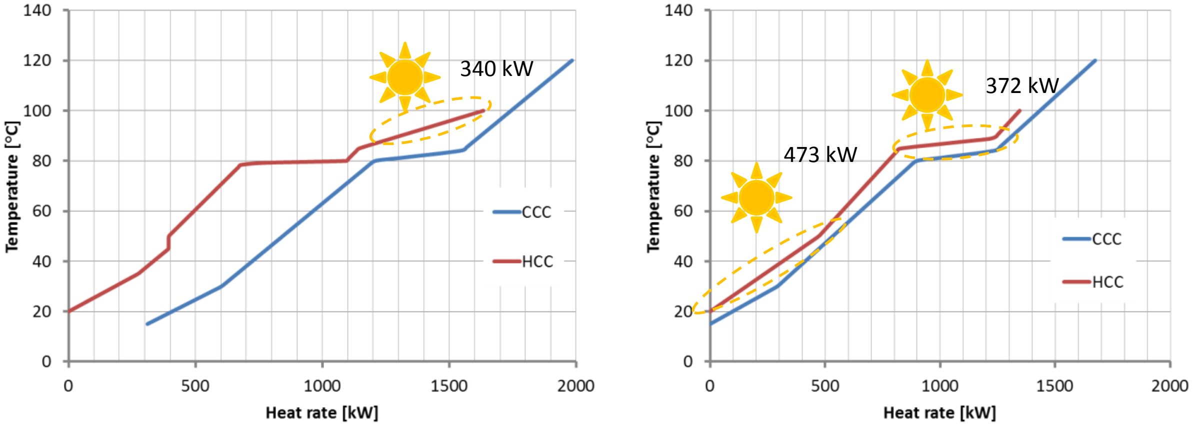


Figure 0-6: **CCs after introducing solar heat as a hot utility stream (selected and sized with the GCC); ΔT_{min} = 5 °C. Left: 340 kW of solar heat 85/100 °C (as seen on Figure 0-5(left) added to the hot CC results in a 340 kW decrease of hot utility (in comparison to Figure 0-2)) Right: CCs for the case depicted in Figure 0-5 (right)**

Appendix B

Process Integration Tools

Taken from: Krummenacher, P. and B. Muster-Slawitsch, "Methodologies and Software Tools for Integrating Solar Heat into Industrial Processes," 13th International Conference on Sustainable Energy Technologies, SET2014- E10049 (2014).

Concerning process integration tools, about ten Pinch Analysis software-based tools are available; a description of their scope and features can be found in Kemp I.C. (2007). The scope of applicability may be very different, some being sophisticated tools addressing specific problems or systems, others covering a broader scope, sometimes at the expense of a lower level of computerization or degree of optimization, or simplified models. A detailed assessment of these tools focusing on their suitability to address solar heat is still under way within the framework of IEA SHC Task 49. It should be mentioned that:

CDU-int, CRYO-int, and DIST-int are specialized tools allowing the simultaneous design and optimization (including heat integration) for new or retrofit, 1) of crude oil distillation systems (CDU-int), 2) of complex refrigeration systems for low temperature gas processing (CRYO-int), and 3) of integrated distillation systems (DIST-int).

ASPEN Energy Analyser, SuperTarget, HEAT-int, and CWB Pinch Analysis are state-of-the-art, general-purpose software tools for the heat integration of continuous processes, for both retrofit and new design. HEN can be designed and optimized either automatically or interactively. HEAT-int may interface with SITE-int, a tool for the design and optimization of site-wide utility systems using total site analysis. Similarly, CWB-Pinch Analysis interfaces with CWB-Total Site Energy Management.

INTEGRATION and Optimal-Heat are also general-purpose heat integration software tools, including in particular advanced techniques and features for automated design and retrofit of existing processes.

EINSTEIN is a tool kit for thermal energy auditing of industries, including a heat recovery analysis and design modules for renewable energy systems. It enables a preliminary solar system design based on the results of process integration and heat exchanger network design. Operating schedules of processes can be defined in details.

OSMOSE is a software platform that manages and interfaces flowsheet simulators, process integration tools, databases (process unit operations, technologies, etc.), various solvers, etc., to simulate, analyze and optimize complex energy systems. The platform is mainly used for academic R&D purposes.

CERES is an open source software tool, including a database of processing units to model the processes, and a database of heat recovery technologies. CERES applies Pinch Analysis with optimization techniques to find the most efficient/profitable pathway to recover heat, and with a special focus on the optimization of utilities including combined chiller-heat pumps, heat pumps, chillers, organic Rankine cycles (ORC), and cogeneration (CHP) units.

Pinch is a general-purpose heat integration tool. Pinch supports batch processes and indirect heat integration with heat storage systems. Affordability, flexibility and ease of use are preferred to the powerful optimization methodologies of other tools (e.g., no automatic design, no retrofit). It also includes spreadsheet models for quick heat & mass balancing of a selection of unit operations.

SOCO delivers proposals of heat exchanger networks and heat storage optimization concepts. It allows simulation, design, and optimization of heat integration solutions for time varying processes (e.g., real measurement data used for simulation, detailed model of heat exchanger and stratified heat storages).

OBI is a software tool targeted to the optimization of processes under variable operating rates and batch conditions. The overall HEN design (merging the HEN specific to each operating case) is generated with one click of a button.

Among this (non-exhaustive) list of tools, few tools address time variable heat flows or batch processes and heat storage at a practice relevant degree: EINSTEIN, Pinch, SOCO, and OBI. Pinch and SOCO model time- dependent processes and heat storage. It is worth noting that so far no single tool implements the whole workflow, and that the time consuming steps consisting of identification, assessment and screening of integration points are neither computerized nor provided with automatic data exchange with process integration tools. These are areas of further work.

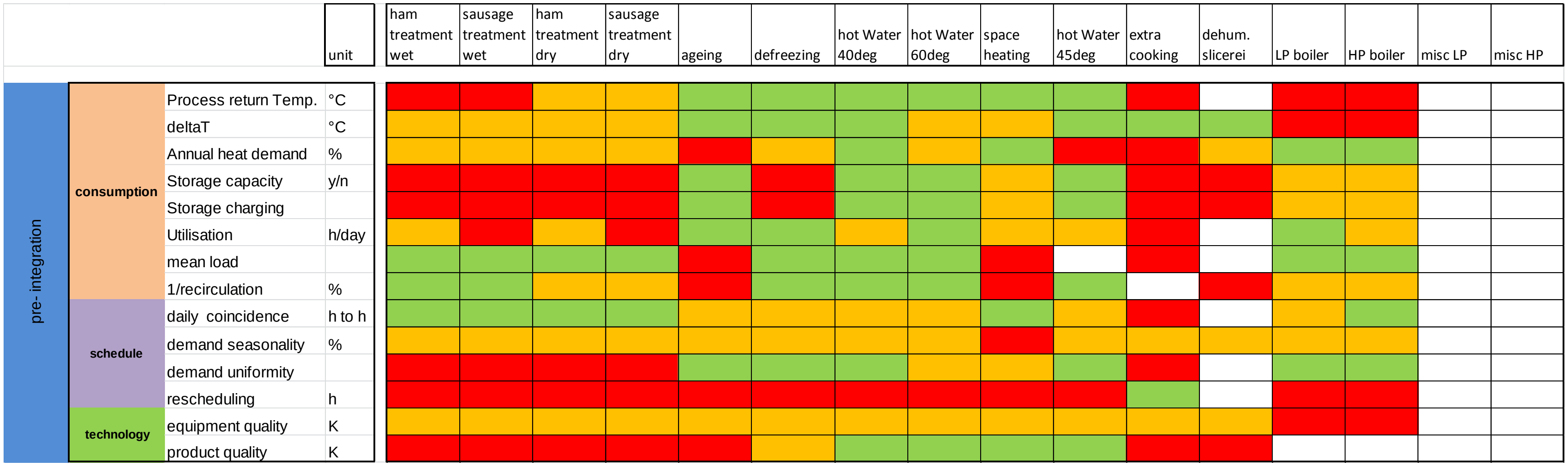
Appendix C

Example for detailed ranking matrix

This section illustrates the ranking matrix for a meat factory. Unlike in section 7.3, one color is assigned for each indicator and integration criterion. In Figure 0-7 all 14 heat sinks are evaluated using the indicators on the left side.

As it can be seen, some sinks could not be evaluated due to missing demand figures. Around 20% of the whole consumption could not be assigned to every sink. During the evaluation, it was recognized that rescheduling is very difficult to evaluate because many parties need to be involved in such a measure. Rescheduling one sink would automatically have an impact on other sinks that cannot be easily quantified. The annual heat demand indicator can be used to filter out sinks with very low share on the whole consumption. It is recommended to first consider this task before evaluating all sinks.

In the second step, different exemplary integration concepts were developed for the five sinks: sausage dry treatment, hot Water 40 degree, hot Water 60 degree, and Low and High Pressure boilers. A set of eight post-integration candidates was obtained as shown in Figure 0-8. The figure also shows the color resulting for each sink from the previous step. By combining the summary colors of step 1 and step 2, a common color per candidate is obtained. While most of the figures needed in step 1 are collected during process integration, step 2 requires a supplementary and intensive analysis of the integration candidates. As mentioned in Chapter 7.4, the final decision strongly depends on the matrix user itself. While the planning engineer will look for candidates close to the solar field, the site operator will first choose candidates that reduce the utilization of the excessively operated LP boiler. The planner may try to achieve high solar gains while the factory owner is only concerned by the process continuity.



			unit	ham treatment wet	sausage treatment wet	ham treatment dry	sausage treatment dry	ageing	defreezing	hot Water 40deg	hot Water 60deg	space heating	hot Water 45deg	extra cooking	dehum. slicerei	LP boiler	HP boiler	misc LP	misc HP
pre- integration	consumption	Process return Temp.	°C	🟥	🟥	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟥	⬜	🟥	🟥	⬜	⬜
		deltaT	°C	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟨	🟨	🟩	🟩	🟩	🟥	🟥	⬜	⬜
		Annual heat demand	%	🟨	🟨	🟨	🟨	🟥	🟨	🟩	🟨	🟩	🟥	🟥	🟨	🟩	🟩	⬜	⬜
		Storage capacity	y/n	🟥	🟥	🟥	🟥	🟩	🟥	🟩	🟩	🟨	🟩	🟥	🟥	🟨	🟨	⬜	⬜
		Storage charging		🟥	🟥	🟥	🟥	🟩	🟥	🟩	🟩	🟨	🟩	🟥	🟥	🟨	🟨	⬜	⬜
		Utilisation	h/day	🟨	🟥	🟨	🟥	🟩	🟩	🟨	🟩	🟨	🟨	🟥	⬜	🟩	🟨	⬜	⬜
		mean load		🟩	🟩	🟩	🟩	🟥	🟩	🟩	🟩	🟥	⬜	🟥	⬜	🟩	🟩	⬜	⬜
		1/recirculation	%	🟩	🟩	🟨	🟨	🟥	🟩	🟩	🟩	🟥	🟩	⬜	🟥	🟨	🟨	⬜	⬜
	schedule	daily coincidence	h to h	🟩	🟩	🟩	🟩	🟨	🟨	🟨	🟨	🟩	🟨	🟥	⬜	🟨	🟩	⬜	⬜
		demand seasonality	%	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟨	🟨	🟨	🟨	🟨	⬜	⬜
		demand uniformity		🟥	🟥	🟥	🟥	🟩	🟩	🟩	🟨	🟨	🟩	🟥	⬜	🟩	🟩	⬜	⬜
		rescheduling	h	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟥	🟩	⬜	🟥	🟥	⬜	⬜
	technology	equipment quality	K	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥	🟥	⬜	⬜
		product quality	K	🟥	🟥	🟥	🟥	🟥	🟨	🟩	🟩	🟩	🟩	🟥	🟥	⬜	⬜	⬜	⬜

Figure 0-7 The pre-integration ranking matrix applied for all sinks

summary pre-integration		🟥	🟩	🟩	🟩	🟩	🟨	🟨	🟨
		sausage dry treatment	hot Water 40deg		hot Water 60deg		LP boiler	LP-HP	HP boiler
		PL_E_PM	SL_S_SC	SL_S_SC	SL_S_SC	SL_S_SC	SL_S_PI	SL_S_MW	SL_S_PI
		external air HX	internal HX	R flow boost	internal HX	R flow boost	indirect SG	makeup W	indirect SG
reliability*	Process continuity	🟨	🟥	🟨	🟥	🟨	🟥	🟨	🟥
	Load balancing	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩
	Control Hardware	🟨	🟩	🟩	🟩	🟩	🟥	🟨	🟥
	Control Software	🟩	🟨	🟩	🟨	🟩	🟥	🟨	🟥
cost	HX sizing	🟥	🟥	🟨	🟥	🟨	🟥	🟥	🟥
	Storage sizing	🟩	🟩	🟨	🟩	🟨	🟥	🟩	🟥
	Distance to solar	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Fouling risk	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Auxiliary energy	🟨	🟩	🟩	🟩	🟩	🟥	🟩	🟥
benefit	Estimated solar yield	🟩	🟥	🟨	🟩	🟩	🟥	🟩	🟥
	Multi-supply	🟥	🟩	🟩	🟨	🟨	🟩	🟩	🟩
	Modulation	🟩	🟩	🟩	🟩	🟩	🟥	🟥	🟨
	Dependency on radiation	🟩	🟩	🟩	🟩	🟩	🟥	🟨	🟥
efficiency	Replacement of CHP	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
	Replacement of WH/HR	🟩	🟥	🟥	🟩	🟩	🟩	🟨	🟩
summary post-integration		🟨	🟥	🟩	🟨	🟩	🟥	🟨	🟥
summary		🟥	🟨	🟩	🟨	🟩	🟥	🟨	🟥

Figure 0-8 The post-integration raking matrix applied for five sink

Appendix D

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