SolarPACES Annex IV

IEA SHC Task 49

Solar Process Heat for Production and Advanced Applications

Methodologies and Software Tools for Integrating Solar Heat into Industrial Processes

Version 2.0, February, 2015

Authors: Pierre Krummenacher, Bettina Muster

Target audience:

This document is primarily intended for the process integration community, and aims to present specific issues of, and solutions/approaches for, the integration of solar heat into industrial processes. It does not describe Process Integration nor present the basics of Pinch Analysis. Readers not familiar with these topics should refer to the Task 49 report, *Integration Guideline*, Chapter 4, which is targeted to the community of solar engineers.

Contents

1 Description of IEA SHC Task 49

1.1 Background

Solar Heat for Industrial Processes (SHIP) has significant potential to cover the useful heat demand of certain industry sectors. IEA SHC Task 49 is working to foster the uptake of this technology.

This report includes a brief introduction on the technical potential of SHIP and then outlines the current status of SHIP applications.

It is well known that the industry sector represents a high share of the final energy consumption in most developed countries. In the EU-28, a quarter of the final energy consumption can be linked to the industry sector.

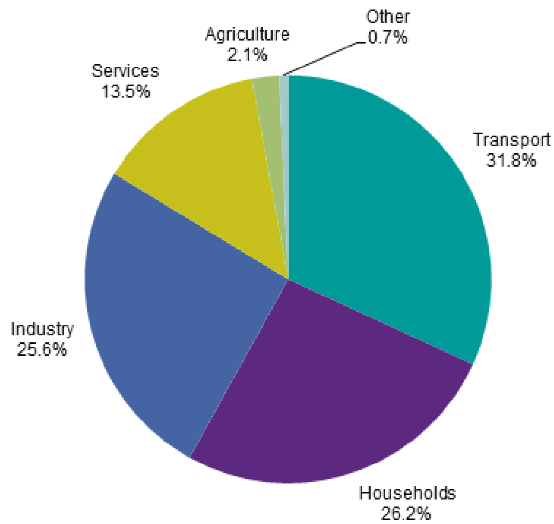


Figure 1: Final energy consumption, EU-28, 2012, Eurostat.

The Joint Research Centre [1] categorizes industrial heat demand into three temperature groupings. Figure 2 shows that the majority of the useful heat demand is required at high temperatures that are out of the reach of conventional solar heat collectors. However, a huge potential remains for low temperature heat demands (< 100°C) that can be delivered using conventional solar heat collectors, and medium temperature heat demands (100-400°C) that can be provided using advanced collector technologies.

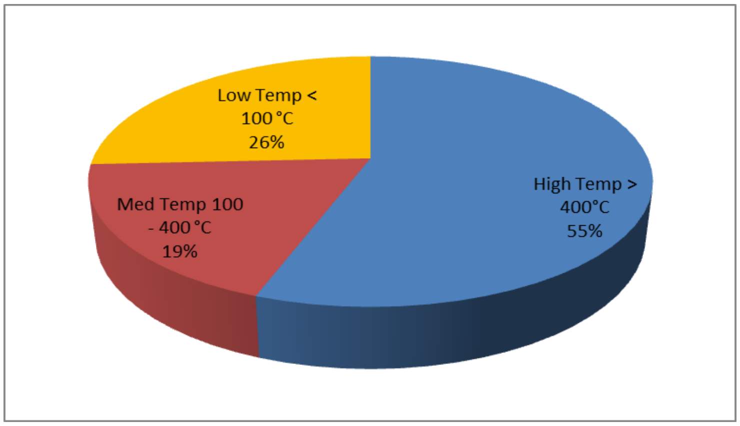


Figure 2: Breakdown of useful heat demand for EU-27 industry in 3 temperature levels.

A closer look at the different industry sectors reveals that the majority of high temperature heat demand exists in the various metal industries (iron, steel, aluminum), non-metallic mineral industries (especially, cement industry) and partly the chemical industry.

The highest demands on low and medium temperature heat come from the food, drink and tobacco industry and the paper and painting industry. It is worthwhile mentioning that the remaining demand is in the chemical industry and the machinery industry because metal processing – which can be assigned to both industry categories – is also an important target for SHIP applications. The production capacity of the textile industry in Europe has dropped dramatically for many years, however, textile processing remains a great potential for SHIP in other regions, such as China and Southeast Asia.

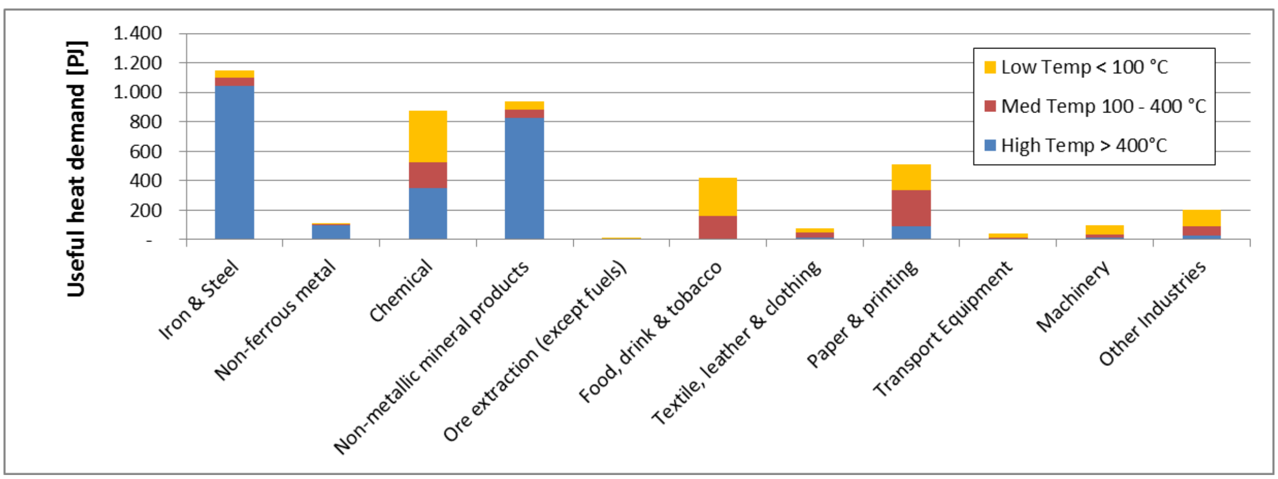


Figure 3: Breakdown of useful heat demand for EU-27 industry for 3 temperature levels for the main industry sectors in Europe.

As part of SHC Task 49, a survey on SHIP applications was conducted. So far 164 SHIP applications have been surveyed, however, only 135 have sufficient data to be published on ship-plants.info. Figure 4 shows the distribution of the SHIP applications worldwide.

Figure 4: Location and number of reported SHIP applications.

According to the SHIP database, 141.355 m² of gross area solar heat collectors for industrial processes are installed worldwide. Most of these systems are experimental and relatively small in scale. However, in recent years the number of very large applications has increased significantly. An example of such a large-scale installation is at a copper mine in Chile, which pushes the country to first place in installed collector area for SHIP.

In total, 20 SHIP applications have a gross collector area > 1000 m², which represents 77% of the total installed gross collector area.

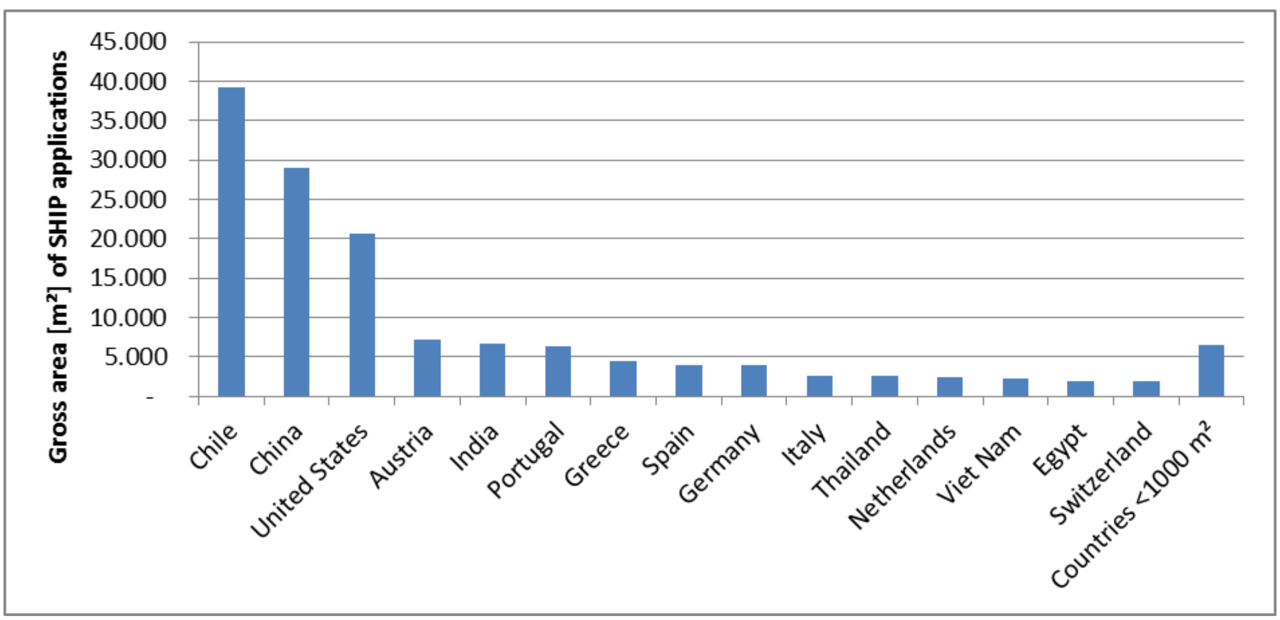


Figure 5: Gross collector area of SHIP applications in different countries.

When tapping into the potential of SHIP it is important to evaluate the thermal processes and the thermal energy supply of the industry site in question. The methodology that has been developed to achieve a thermal energy supply in industry with minimal greenhouse gas emissions is based on a three-step approach:

1. **Technological optimization** of the processes (e.g., increased heat and mass transfer, lower process temperature) and solar thermal system (e.g., operation of solar field, integration schemes, control, safety issues, etc.).
2. **System optimization** (enhancing energy efficiency using, for example, Pinch Analysis for the heat exchanger network of a total production site).
3. **Integration** of renewable energy/solar thermal energy (based on exergetic considerations).

Over the last two years, the awareness for solar process heat in industry has increased and new solar thermal systems have been installed as noted above. This positive development should now be supported by further research and development in the key research questions of solar process heat.

After completion of the IEA SHC Task 33/SolarPACES Annex IV, key areas for further technological development, which should be treated in the context of a new Task, were identified:

- Process heat collector development with heat loss control and maximization of energy collection;
- Material research with improvement of components on a higher temperature level and better materials for concentrated optics; and
- Process heat collector testing for working temperatures above 100°C.

The content of the current IEA SHC Task 49 were defined based on this knowledge out of IEA SHC Task 33/SolarPACES Annex IV and other position papers, such as the strategic research agenda of the European Solar Thermal Technology Platform and the experience of several national projects in the field of solar process heat.

1.2 Task objectives

Subtask A: Process Heat Collectors:

- Improvement of solar process heat collectors and collector loop components
- Comparison of collectors with respect to technical and economic conditions
- Comprehensive recommendations for standardized testing procedures

Subtask B: Process Integration and Process Intensification combined with Solar Process Heat:

- Development of advanced pinch and storage management tool(s)
- Survey on integration methodologies for solar process heat
- Develop System concepts and integration guideline
- Survey and dedicated Workshop on new process technologies
- Identification of the increasing potentials and compendium of on going activities and existing pilot plants/case studies

Subtask C: Design Guidelines, Case Studies and Dissemination:

- Design guidelines
- Simulation tools
- Performance assessment methodology
- Monitoring of demonstration projects and “best practice” projects

- Dissemination of Task results
- Market deployment
- Potential study

1.3 Task 49 scope

Applications, systems and technologies that are included in the scope of this Task are:

- All industrial processes that are thermal driven and running in a temperature range up to 400°C.
- Solar thermal systems using air, water, low pressure steam or oil as a heat carrier, that is not limited to a certain heat transfer medium in the solar loop.
- All types of solar thermal collectors for an operating temperature level up to 400°C are addressed: uncovered collectors, flat-plate collectors, improved flat-plate collectors - for example hermetically sealed collectors with inert gas fillings, evacuated tube collectors with and without reflectors, CPC collectors, concentrating collectors with stationary receivers, parabolic trough collectors, Fresnel collectors, etc.
- Technologies for industrial application that can be driven by sunlight or specific spectrums (e.g. UV).

Specific process engineering technologies to which solar heat has to be supplied, such as technologies for desalinating seawater, industrial cooling applications and electricity generation are not the main focus of the Task. They may be considered to a certain extent if there is strong interest from industry.

For cooling applications, the work will be restricted to the adaptation of the results of IEA SHC Task 38 to industrial applications.

The foreseen activities in the field of heat storage management will not deal with the development of storage technologies and the application of new storage materials. This work will be addressed in IEA SHC Task 42 and its follow-up activities.

There is a link of IEA SHC Task 49 to the activities in IEA SHC Task 45 on large scale systems due to the size of the solar thermal systems and the challenges faced by both applications. The main differences between IEA SHC Task 49/IV and IEA SHC Task 45 can be seen in:

- Dependence of the solar thermal system design on the industrial process layoutCombination of process intensification and solar thermal systems
- Dealing with new applications
- Different temperature levels (SHIP up to 400°C) and more relevance on the development and application of concentrated systems
- Based on the higher temperatures different challenges on material, fluids, collector and components behavior are considered
- Different stagnation behavior due to batch processes and different hot storage management
- Detailed focus on industrial processes in combination with solar thermal collectors.

1.4 Task 49 Subtask B, activity B1: Development of advanced pinch and storage management tool(s)

The general methodology for the integration of solar thermal energy into industrial processes was developed during IEA SHC TASK 33/SolarPACES Annex IV. It was shown that the Pinch analysis for the total production site and - building upon it - the design of an optimized heat exchanger network for the production system is one of the best approaches for an intelligent integration. Due to the fact that in the identified industry sectors with high potential for solar integration there are very often production processes running in batches, the developed Pinch methodology can only be a rough estimation of the real profile of heat sources/sinks. Additionally, it has been proven that the adaptation of existing heat management strategies (operation of heat storages) can help to integrate solar thermal plants more efficiently. In order to fulfill these needs of further improvements to model the real heat management of a production system it is necessary to further develop the existing methodology and software tools. This advanced process integration will additionally consider time dependency of the production profile, the integration of heat storages and the optimized design and management of all heat flows within the production system. The aim is to reach further reduction of the companies' energy demand and an ideal condition for solar integration.

Bringing together the know-how and expertise of several experts dealing with heat integration and heat management tools, several tools have been compared. Also, new tools are being developed with the aim to identify ideal integration places of solar heat in industrial processes.

2 Integration methodologies of solar heat into industrial processes

2.1 Combining solar heat with energy efficiency actions

Long term energy consumption and CO_2 emissions reduction targets have been announced in various countries. For example, according to the "Roadmap for moving to a competitive low carbon economy in 2050" [2], the European Union targets at a reduction of approx. 80% of greenhouse gases (GHG) emissions until 2050 (compared to 1990). These ambitious goals will only be met by a holistic approach combining energy efficiency measures with renewable energy resources. Analyzing the status of implementation of the energy efficiency potential in industry (e.g. see energy efficiency index ODEX of the EU-27, European Environment Agency, 2011) reveals that it will be vital to focus in first priority on energy efficiency measures to maintain a competitive European manufacturing industry. As far as thermal energies are concerned, this can be efficiently addressed resorting to Process Integration (PI) methodologies, and in particular to Pinch Analysis [3], [4], a proven, systematic and efficient methodology to target and design optimum heat integration solutions, improving the energy efficiency significantly beyond traditional approaches to heat recovery designed by trial & error.

Indeed, despite the more stringent legal framework, the shrinking of fossil energy resources and the claimed energy efficiency of process facilities, industrial plants seldom run at minimum energy consumption (more precisely at minimum fossil exergy consumption). And regarding thermal energy, Pinch Analysis often reveals improvement potentials typically in the range 10 to 40%, with payback not exceeding 3 years, even without technology changes. Referring to the ambitious long-term targets, an energy efficient and cost-effective substitution of fossil heat by solar heat strives to design the solar system in priority for operating temperatures as low as possible [1]. However, industrial processes often feature on the one hand low-grade heat in excess, and on the other hand, consumption of high grade heat to supply low temperature heat sinks. Supplying the latter with solar heat instead would probably be inadequate because heat recovery of excess heat is often more cost effective.

Process Integration is the appropriate framework to address these issues and to optimally combine heat recovery actions, process modifications/intensification, and solar heat. This ensures in particular:

- Scoping and screening of most promising scenario / alternatives, including solar heat supply,
- Optimizing size and selection of operating conditions of the solar plant (e.g., operating temperatures as low as appropriate),
- Increased energy and CO_2 reduction, and
- Increased profitability / shorter payback of the solar heat integration project thanks to the compensation effect of heat recovery measures featuring much shorter payback.

2.2 Solar heat – a special hot utility / heat source

Unlike fossil fuel based utilities, the solar radiation resource varies stochastically: its intensity and "quality" (e.g., direct to global radiation ratio) are not predictable on the short term. The efficiency of the radiation-to-heat conversion depends on the applied solar collectors technology and, given a technology, on parameters of the specific collector type. The efficiency of solar collectors depends on the operating temperature (mean temperature of the absorber) with respect to the ambient

[1] Note that, e.g. in the food industry sector, about 60% of the heat demand is actually required below 100°C.

temperature, (referred to the intensity of radiation) as exemplified in Figure 6.

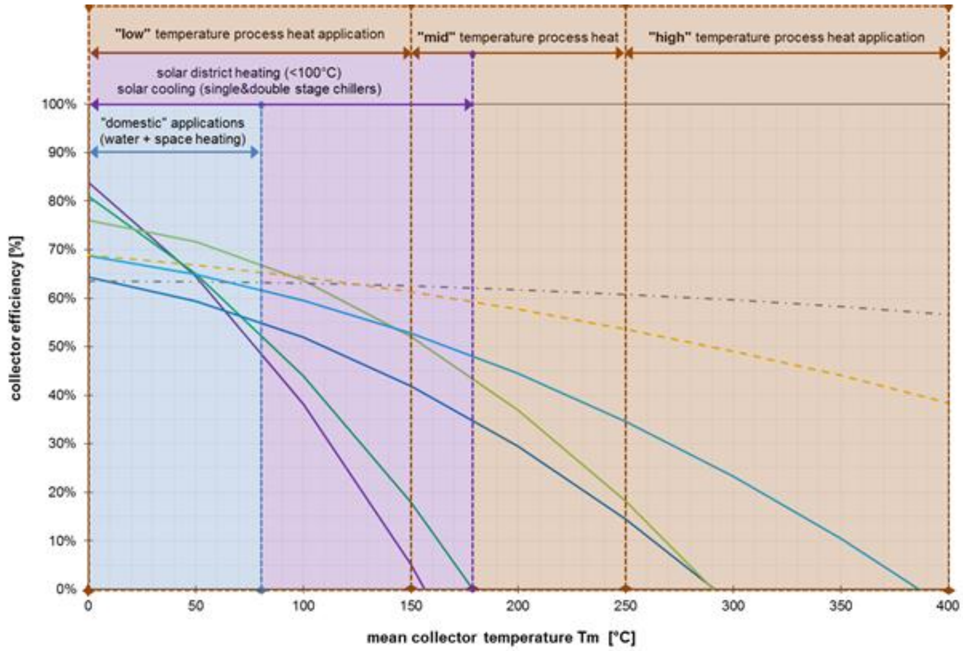


Figure 6: Typical efficiency curve of different collector technologies (AEE INTEC, 2013).

Hence, analyzing and designing the integration of solar heat into industrial processes requires that process integration methodologies and tools must be able to:

- Cope with and to model the time variability of solar heat (requiring typically time resolution <1h) in intensity and temperature, and
- Handle and manage heat storage systems for leveling out the fluctuations of resource.

These requirements so far are challenging the existing methodologies and tools, especially the relevance of calculations for practice.

2.3 PI methodologies extended to renewables – a short review

The general assessment methodology for solar process heat (as defined by IEA SHC Task 49 [5]) highlights the fact that the consideration of process integration opportunities should be done prior to the consideration of solar heat integration. This has already been stated by H. Schnitzer and colleagues [6], within IEA SHC Task 33 [7], and been tackled by recent guidelines, such as the SoPro guideline for solar process heat [8] and the EINSTEIN methodology and its tool [9]. The core reason is that process integration measures have effects on the heat demand, for example, process modifications can lead to lower process temperatures, better control can realize smoother process profiles, etc. Such measures would enhance the possibility to integrate solar heat. On the other hand, the possible use of available waste heat has to be ensured and other energy efficient technologies, such as heat pumps, might shift the threshold for solar heat to higher temperatures.

In the Process Integration R&D community, the consideration of renewables has emerged as a research topic in recent years. The stochastic variability of renewables, and the variability of heat demand (e.g., semi-continuous or batch processes, space heating, etc.) are a matter of particular concern – how to handle them in analysis, design, and operation? Several publications, reviewed in the *Handbook of Process Integration*, Chapter 7 [10], focus on the integration of renewables at the utility level and analyzed using the Total Site Integration methodology. Perry and colleagues [11] apply the Total Site Integration methodology to integrate waste and renewable energies in locally integrated energy sectors (LIES) to reduce the carbon footprint of supplied small-scale industrial plants, domestic, business and social premises. However, the variability of renewables is not considered.

Varbanov & Klemes [12] propose a methodology for designing and operating energy conversion & supply systems integrating renewables featuring variable availability, as well as timely variable users. The Total Site Integration methodology is combined with the Cascade Analysis originally developed for batch processes, into a Total Site Heat Cascade. The methodology allows for, in particular, the determination of important targets, such as the upper bound of renewable capture, the lower bound of fossil fuels consumption, and the upper bound of energy storage. The time variability (of renewable resources and/or of user demand) is modeled by a set of time slices, a cascade being calculated for each time slice, considering heat storage that allows cascading heat to a later time slice. The optimization of heat storage is mentioned as one of several further steps to follow.

Also relevant for the integration of solar heat are publications on the site-wide heat integration resorting to heat recovery loops (HRL) with heat storage (HS) ([13], [10] Chapter 20). This is appropriate for low pinch temperature industry sectors (examples are food and beverage sectors) and large multi-plant sites using large amounts of hot water and operate semi-continuously. As shown by Walmsley and colleagues [14], the existence of the HRL-HS infrastructure represents an opportunity to reduce the costs for integrating solar heat, since the HRL-HS costs can be shared for both the heat recovery between processes and the solar heat distribution. The authors compare two strategies for designing and operating the HRL-HS system (constant temperature storage (CTS) versus variable temperature storage (VTS)) for different pinch temperature positions (hot “end” of heat source profile versus cold “end” of heat sink profile). Results show that the VTS strategy is more cost-effective, in particular with respect to the integration of solar heat when the pinch between heat source and heat sink profiles is located at the hot “end” of the heat source profile.

2.4 Overview of solar heat integration modes and concepts

The integration of solar heat into industrial processes may be achieved at two different “levels”:

1. Transfer of solar heat “directly” to individual process heat sinks – referred to as integration of solar heat “on process level”
2. Transfer of solar heat to the hot utility system (e.g., steam system, superheated water, thermal oil, etc., and then in cascade to process heat sinks by utility-process heat exchangers) referred to as integration of solar heat “on supply level.”

Each integration level has its advantages and drawbacks. IEA SHC Task 49’s *Integration Guideline* [5] provides a detailed comparison. In short, the integration at the process level allows in general lower collector operating temperatures. But due to the variability and partially out of phase availability of solar heat, heat storage is required in most cases and the solar fraction may be limited to the heat demand of one or of few heat sinks located very close to each other (retrofitting the process heat supply infrastructure and building a dedicated loop for distributing solar heat would induce significant investment costs).

Unlike the process level integration, integrating at the supply level is more flexible because the pay off of the solar plant is much less dependent on possible future changes in individual processes. Furthermore, this mode can achieve a larger solar fraction with smaller specific costs (due to potentially smaller heat storage requirements and to the availability of the utility infrastructure for heat distribution) at the expense of higher operating temperatures.

The supply level integration can apply to two types of networks: solar heat can be fed into the utility system or into the HRL-HS system (if it already exists or if this type of system is a cost-effective retrofit option for multi-process indirect heat integration).

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 in the collector as well).

A systematic classification of the possible integration concepts was developed by B. Schmitt [15] for the practical integration schemes for both process level and supply level integration. IEA SHC Task 49 report, *Integration Guideline*, Chapter 6 [5] presents the classification established based on the following boundary conditions:

- 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

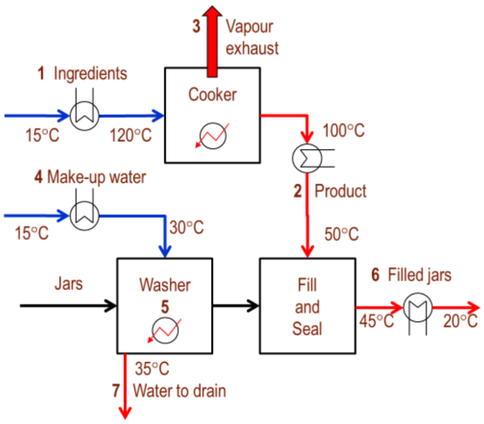
In addition, given an integration concept then a solar process heat system concept must be chosen. IEA SHC Task 49 report, *Integration Guideline*, Chapter 7 [5] describes the topic, including strategies and hydraulic designs for collector loop, storage charging, storage interconnection and storage discharge.

2.5 A simple example process

The preliminary analysis of process level integration is exemplified by means of a simple process derived from [16], whose flowsheet is represented in Figure 7(left); it has been purposely modified to demonstrate some aspects addressed in this document.

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.

The list of process heat sources and heat sinks of the food packaging line is presented in Figure 7 (right), taking the following constraints and opportunities into account. It is assumed that the cooker cannot be modified at affordable costs for heat integration so that it must beis still supplied by steam and therefore is not included in the list of heat sinks for analyzing the heat recovery (to be fully consistent it should be represented as a heat sink in the form of steam to analyze the heat integration of utilities). However, the steam consumption can be reduced if ingredients are heated (if possible up to 120°C) before entering the cooker – at present, the ingredients are not preheated and 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. In addition, at present, make-up water is not preheated, but it is assumed it could be preheated up to 30°C (the rest being achieved by the existing internal heat recovery), in which case the water to drain would leave at 35°C. Considering the inlet temperature of ingredients and washer make-up water of 15°C, the washer water flow to drain could be cooled down to around 20°C if needed.

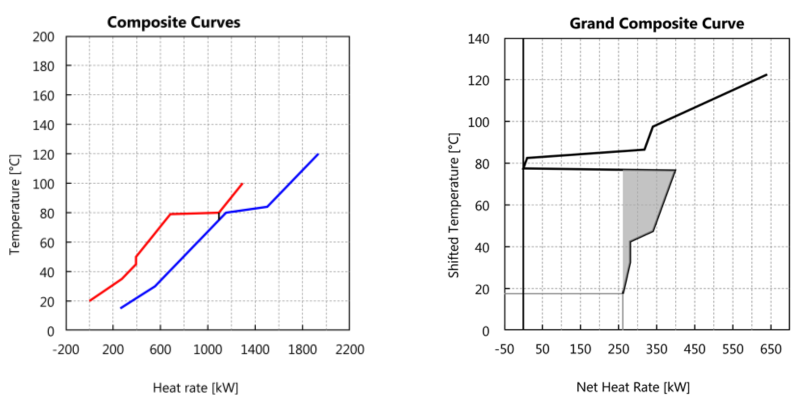


#	Name	T_{in} [°C]	T_{out} [°C]	Flow [kg/s]	c_p [kJ/kg^{-1}K^{-1}]	Heat rate [kW]
1	Ingredients heating	15	120	4.0	3.0	1260
2	Product cooling	100	50	3.6	2.778	500
3	Vapour condensation	80	79	0.4	1000	400
4	Washer make-up water	15	30	1.8	4.18	112.86
5	Washer lye bath holding	80	84	17.943	4.18	300
6	Filled jars cooling	45	20	6.0	2.0	300
7	Washer water to drain	35	20	1.5	4.18	94

Figure 7: Process flowsheet (left) and corresponding list of process heat sources and heat sinks (right) of the food packaging line example process.

2.6 *Scoping and screening process integration opportunities*

Scoping and screening of process integration opportunities is achieved using the process Composite Curves (CCs) and the Grand Composite Curve (GCC). The possible integration of solar heat at process level (as a special heat source) adds another technology alternative to the set of possible technologies, exclusively or in combination with other technologies. Figure 8 presents the base case CCs, GCC, and the corresponding targets, assuming $\Delta T_{min\ opt}$=5°C and no limitation to heat transfer between heat sources and heat sinks as needed (vertical heat transfer from hot to cold CC, respectively heat transfer under $\Delta T_{min\ opt}$=5°C for GCC).



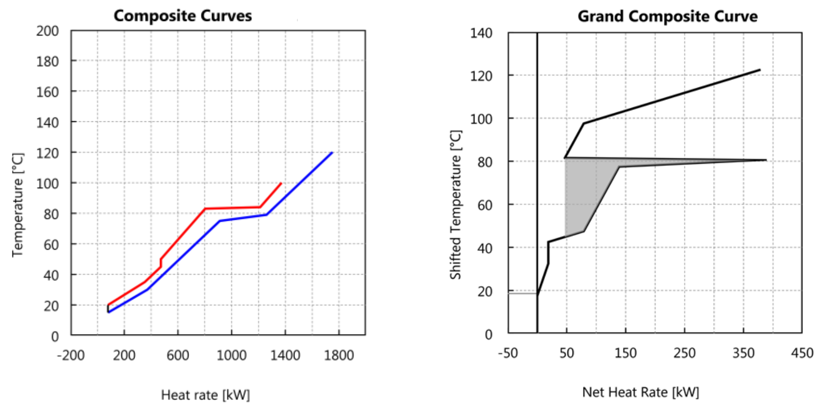
Target values

Heat recovery = 1033 kW

Hot utility = 640 kW

Figure 8: CCs (left) at ΔT_{min}=5°C and corresponding GCC (center) – base case.

Considering the shape of CCs, the heat recovery could be increased if the temperature of the lye batch is decreased by at least 5 K (e.g. by optimizing the detergent, etc.) or the condensation temperature of exhaust vapor is 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 both. 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. Figure 9 represents the CCs and GCC assuming a decrease of 5 K of the lye bath operating temperature as well as 4 K increase of the condensation of vapor. $\Delta T_{min\ opt}$=5°C as for the base case.



Target values

Heat recovery = 1294 kW

Hot utility = 379 kW

Figure 9: CCs (left) at ΔT_{min}=5°C and corresponding GCC (center) – after lowering lye bath heating and increasing vapor condensation temperatures.

If however, process modifications are not feasible, the engineer identifies from the GCC analysis at least three possible scenarios to supply heat to the process to be compared (at least as regards the 340 kW of heat deficit below 100°C): Scenario 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 washer lye bath; Scenario 2: A cogeneration unit based on an internal combustion engine; and Scenario 3: A solar heat supply.

Figure 10 represents Scenario 1, the integration of a compression heat pump matched against the GCC, and the resulting CCs and GCC (261 kW evaporator stream at 74°C added to cold CC, 276 kW condenser stream at 89°C added to hot CC. The heat pump increases the heat recovery very efficiently (e.g. $COP_{heating}$=16 with refrigerant R245ca) and reduces the heat deficit in the range 85°C to 100°C considered for Scenario 3. Hence, Scenario 1 is a strong competitor to Scenario 3. As discussed below for Scenario 3 as well, costs considerations in retrofit case shall likely lead to match: 1) the condenser stream with the lye bath heating only, giving up matching with ingredients heating too); 2) the evaporator exclusively with vapor condensation (giving up cooling product as well).

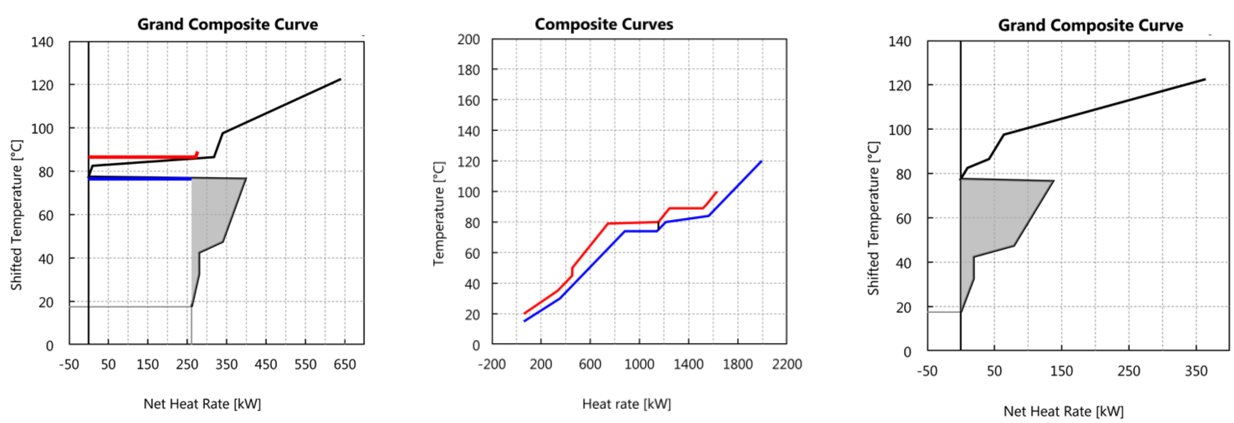


Figure 10: Heat pump matched against GCC (left), CCs after heat pump streams integration, but not yet deciding evaporator and condenser heat transfer matches (center), and GCC after taking out actual evaporator and condenser heat transfer matches (right) – Scenario 1 involving a 276 kW compression heat pump.

Figure 11 represents Scenario 3, the potential integration of 340 $kW_{average}$ [2] solar heat at a temperature level matched against the GCC (85°C to 100°C) [3]. As can be seen on the CCs including the solar heat source, solar heat should supply both the lye bath holding (300 kW) and ingredients heating (40 kW) streams. Partial heating of ingredients may not be economical in a retrofit situation [4] so that solar heat contribution should be reduced to 300 $kW_{average}$ to achieve a profitable heat integration with minimum modifications to heat transfer equipment.

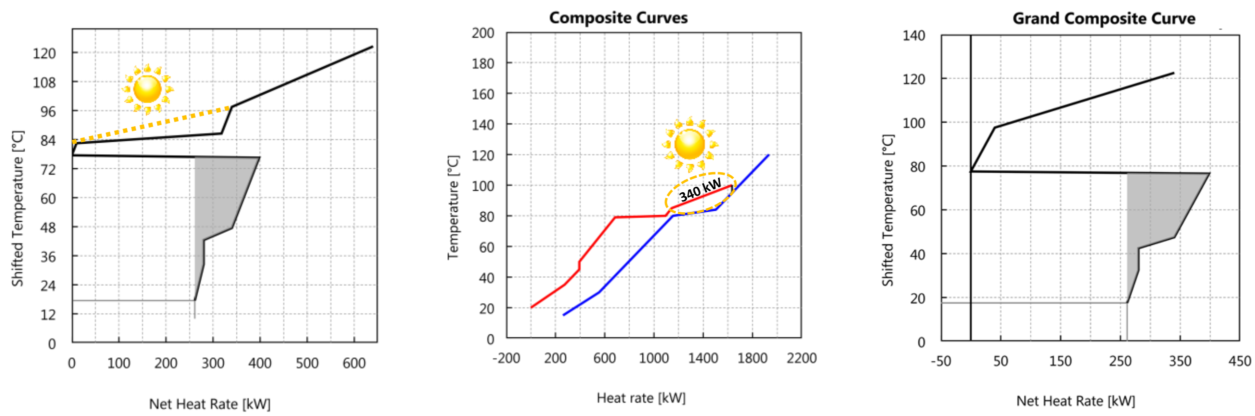


Figure 11: Solar heat integration (340 kW) matched against GCC (left), CCs after 340 kW solar heat integration (center), and GCC after taking out 300 kW solar heat supply actually matched with lye bath (right) – Scenario 3 solar heat supply.

Ideas for additional scenario may come up during the CCs / GCC / CCs steps therefore, iterations are often needed to analyze, generate and evaluate the most promising alternatives. Note that the comparison of scenarios should be based on fully balanced composites (and not partially as done here for the sake of simplification).

If, for whatever reasons (fouling, distance, temperature control, safety hazard, etc.), some streams (e.g., waste heat soft streams) are not suitable for heat transfer as implied by the balanced CCs, the concerned streams must be excluded from the streams list and the heat integration analysis be based

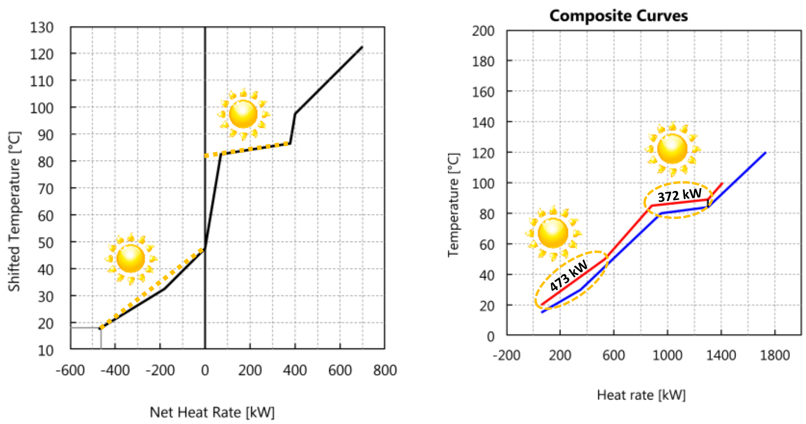
[2] $kW_{average}$ means design solar heat rate on a sunny sommer day, averaged over the design heat storage period (typically a day, depending on the variability of heat umbalance between solar supply and heat demand and the economics of heat storage).

[3] Why not size and design the solar plant to supply the whole heat requirement up to 120°C instead? For the operating temperature, the engineer's preliminary decision, based on experience, depends on the plant location: in regions featuring high direct to global radiation ratio, concentrating collector technologies may be used and high collector operating temperatures can be envisaged a priori, whereas in climatic regions featuring a large diffuse radiation fraction, the cost-effectiveness of concentrating collector (which make use of direct radiation only) may be too limited. In the latter case, flat plate collectors are a preferred option, but with the constraint that the mean collector temperature should be limited to lower values, hence decreasing the average solar heat rate correspondingly as given by the GCC. Ingredients heating from 80 to 120°C prior to cooker inlet would not be achieved (either by heat recovery or solar heat) and be heated in the cooker by steam.

[4] Almost all SHIP projects so far involve adding a solar heat plant to an existing industrial site. The corresponding constraints make the search for energy efficient and reasonably cost optimal solutions a complex combinatorial problem (several process and utility integration alternatives, as well as several integration points for solar heat, subject to solar plant site specific constraints as well as layout of existing processes and utilities infrastructure). The Pinch Analysis based methodology allows restricting the search for solar integration to most promising options while ensuring that other cost-effective alternatives aren't overlooked. After this preliminary screening of the appropriate placement of solar heat, several integration points may be analysed and compared with respect to different criteria, taking practical constraints into account [5].

on recalculated CCs as well as GCC.

The CCs and GCC of the base case depicted in Figure 8 include cooling of filled jars, condensation of cooking vapor, as well as washer wastewater heat recovery. In case these heat recovery opportunities will not or cannot be implemented (heat recovery from filled jars requires an intermediate heat carrier and operators might refrain from vapor condensation and wastewater due to fouling problems) – below referred to as "restricted HR case", the GCC has to be re-drawn after the respective streams have been eliminated, as shown in Figure 12 (left).



372 kW (max) solar heat 84/89°C: candidate process heat sinks:

Ingredients heating = 72 kW

Washer lye bath holding = 300 kW

473 kW (max) solar heat 20/50°C: candidate process heat sinks:

Ingredients pre-heating = 360 kW

Washer make-up water = 113 kW

Figure 12: Solar heat integration (two temperature levels) matched against GCC (left), and CCs after solar heat integration (center) – restricted HR case, with solar heat supply.

The GCC then looks very different. The process 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. On the GCC of Figure 12, the drafted dotted lines represent the maximum possible solar process heat supply below 90°C, split into two temperature levels: 20/50°C, and 85/89°C.

Again, if solar heat is to be supplied at process level, it can be seen on CCs that the low temperature (20/50°C) solar heat supply should ideally be matched with both ingredients pre-)heating and washer make-up water pre-heating, while the middle temperature (85/89°C) solar heat supply should be matched with washer lye bath holding and ingredients heating. Restricting to a single solar-process heat transfer match per temperature level to strive to an economic retrofit would decrease the solar heat contribution (e.g. ingredients pre-heating: 360 kW instead of theoretically 473 kW for 20/50°C loop, and washer lye bath holding: 300 kW instead of 372 kW).

Instead, the designer can consider another scenario and opt for supply line integration, which has the additional benefit of being more flexible. One option, if possible, could be to integrate solar heat into the return line of the existing supply line (e.g. preheating the condensate prior to the boiler). However, this might be at a higher temperature in comparison to the process temperatures depending on the pressure of the existing steam supply, which is not visible in the process GCC.

From a methodology point of view, supply line integration is not as simple as drafting solar heat duty against the process GCC, especially if the integration of utilities is optimized at the same time. A mathematical framework has been proposed by Maréchal and colleagues [17], [10] Chapter 27, to determine the optimal flows of the different utilities of the energy conversion system which minimize the costs (or other objective functions) of supplying the energy requirements, for different pre-selected "blends" of energy technologies on the basis of the process GCC (one of these utilities could be solar heat). The temperature differences between utility supply and process requirements as well as corresponding exergy losses can be analyzed. The so-called Integrated Composite Curves are an appropriate graphical representation for this analysis. The methodology is implemented in some software tools; it could be extended to account for the integration of solar heat.

Scoping & screening process integration scenario – summary

- Major conceptual opportunities for integration of solar heat can be scoped and screened (as other process integration opportunities) using the CCs and GCC diagrams. Solar heat integration may complement, or compete, with other process integration actions.
- Placing and sizing the solar heat duty against the GCC is only a rough preliminary assessment due to:
  - The stochastic time variability of solar heat in terms of temperature and heat duty,
  - Technical constraints / limitations to heat recovery not apparent / not taken into account at the onset, and
  - Economic constraints in retrofit situation limiting the number of solar heat-process heat sink matches in case of process level integration.
- After the analysis of process GCCs and CCs, opportunities of solar heat integration at supply level can be checked / analyzed in more details using other diagrams such as e.g. integrated composite curves, total site profiles, indirect source & sink profiles (ISSP) in case indirect heat recovery loops are an option [13].

The above steps allow the identification of promising integration points of solar heat, but further assessment and comparison of candidate integration points is needed, as stated in Section 2.4.

Notes:

- After solar heat supply (as well as other utilities) have been drafted based on the GCC, two routes may be followed:
  - A. Analysis and pre-screening of possible integration points (i.e. finding the heat sinks to be supplied by solar heat) on the basis of CCs, later followed by the application of heat exchanger and heat storage optimization algorithms;
  - B. Application of heat exchanger and heat storage optimization algorithms.

  Following Route A first makes sense for continuous processes because the time variability only stems from solar heat, and/or when visual identification of suitable heat sinks to define the integration points is needed to get insight into and to assess the relevance of different integration points (unlike the GCC, the CCs are meaningful for non-experts and can be easily related to actual streams).

  Going directly to Route B is recommended in the case of a significant time variability of the process itself, possibly making a representation of time average CCs too crude a simplification.
- As for all graphical curves in the 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 [18], [19]. For the latter, different CCs in different time slices can be used as a basis to evaluate how the pinch point changes over time and whether this might influence the decision for the integration of solar heat.
- To visualize the real variations of solar heat these time steps should be less than 1 hour. Other process variabilities (e.g., in start-up phases, batch processes) might require even smaller time steps. In this case the visualization of CCs can only be done with an interactive scroll bar over time. 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.

2.7 Practice relevant HEN & heat storage design

Once $\Delta T_{min\ opt}$ has be defined and the CCs are balanced by utilities, the heat integration modeled by the balanced CCs must be realized by a feasible and cost optimized heat exchanger network (HEN). During the last 30 years, numerous methods for HEN design have been developed [20], ranging from design by hand using 2 steps-heuristics, such as the original Pinch Design Method, to automatic design & optimization using Mathematic Programming (MP) or Evolutionary Algorithm (EA) techniques to optimize various objective functions, as well as design methods combining insight provided by Pinch Analysis and MP optimization techniques for their efficient and quick search for solutions.

For semi-continuous and batch processing, the analysis has so far been mostly divided into time slices. Few methodologies can actually design HEN for time dependent processes and at the same time manage heat storage. Heat exchanger and heat storage network design algorithms for variable process streams are now required and are a strong tool for identifying and comparing process integration measures, as they translate the thermodynamic potential to practical solutions [21].

For solar process heat design it becomes clear that the tools offered by Pinch Analysis are powerful for first considerations, 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 this 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
- Re-design this network due to solar process heat integration.

This re-design including solar heat can integrate solar heat 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 storage network (HESN) design are activated.

Such algorithms may then suggest solar integration points to achieve highest 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 13 shows an exemplary scheme of a heat integration concept including solar heat as utility. System simulations then allow to design 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. Such an approach has been achieved within the SOCO software tool (see Section 3.2).

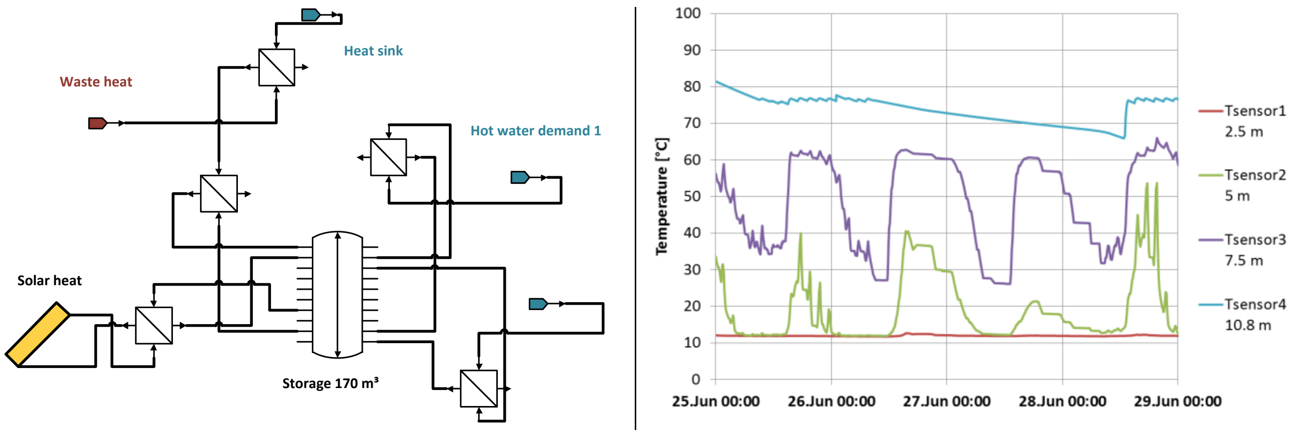


Figure 13: Flowsheet in SOCO which can be simulated to evaluate the performance of heat exchangers and storages (on the right) over time; combinations of solar heat and heat recovery can be analyzed.

While recent process integration tool developments are starting to include capabilities for thermal heat storage so far no tools combine process integration algorithms with solar simulations. This is an area for future work.

3 Workflow for integration of solar process heat and process integration software tools

A general methodology for solar heat integration has been set up within the framework of IEA SHC Task 49 [5], building on the experience of recent R&D projects. It includes nine stages divided into three main parts: 1) Pre-feasibility assessment, 2) Feasibility study, and 3) Decision making & detailed planning. The workflow presented below covers three stages of part 2, namely: A. Process optimization & energy efficiency, B. Identification and ranking of integration points, and C. Analysis of integration points.

The workflow of the Pinch Analysis based methodology extended to the integration of solar process heat as previously described, is depicted in a synoptic way in Figure 14 for process level integration (while the supply level integration, total site integration and integration into heat recovery loops call on more complex graphical representations and calculation methods). The workflow is to a large extent iterative for scoping and screening. Each iteration loop includes typically three steps (the so-called AGE methodology of F. Maréchal):

1. Analysis of heat integration problem (notably using appropriate graphs, often CCs and GCC, but potentially also other graphs (total site profiles, etc.) depending on the process type and the issues to be analyzed.
2. Generation of alternative solutions as a result from insight and ideas developed during the analysis step.
3. Evaluation and comparison of the performances of alternative solutions.

A fourth step could consist of changing/adapting the problem based on the conclusions of the evaluation step.

These steps can essentially be achieved by the engineer manually, for example, based on simplified models for targeting (if possible), or carried out automatically using optimization algorithms.

The workflow does not represent the following two important input data sets 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.

Integration concepts may vary according to process specifications, existing heat transfer technologies and options to place additional heat exchangers (e.g. indirect heating vs. direct heating). On the process side, a systematic classification of integration concepts depending on the type of heat consumer (process) and the conventional way of heating has been developed in the frame of IEA Task 49 and of a PhD dissertation by B. Schmitt [15]. On the solar supply side, a classification of solar process heat system concepts has been defined by A. Helmke and S. Hess [5]. The system concepts include the following functions of the solar plant towards (but excluding) the integration point: 1) Collector loop, 2) Charge, 3) Storage and 4) Discharge.

For the analysis of integration points, a list of indicators and a list of criteria have recently been developed by I. Ben Hassine within the Integration Guideline of the IEA SHC Task 49 [5]. They only apply once the integration concept and the solar system concept have been defined for each integration point. The list of quantitative indicators relates to the significance and schedule of the heat demand, as well as to the resilience to temperature fluctuations, and allows a first evaluation step. A second evaluation step is based on the ranking of integration points with respect to a qualitative assessment of criteria covering the following families of issues: reliability, cost, benefit, efficiency. The list of criteria can be seen as a checklist of important issues not to be forgotten.

Concerning the tools implementing part of the workflow, about ten Pinch Analysis based software tools are available. A description of their scope and features can be found in [22]. 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 in the frame of IEA SHC Task 49. Tools include:

- 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 Analyzer, 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 allows flowsheet simulators, process integration tools, databases (process unit operations, technologies, etc.), various solvers, etc., to communicate together 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 data base of heat recovery technologies. CERES applies Pinch Analysis with optimization techniques to find the most efficient / profitable pathway to recover heat, and 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 at 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 are described in more details below. These two tools manage 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.

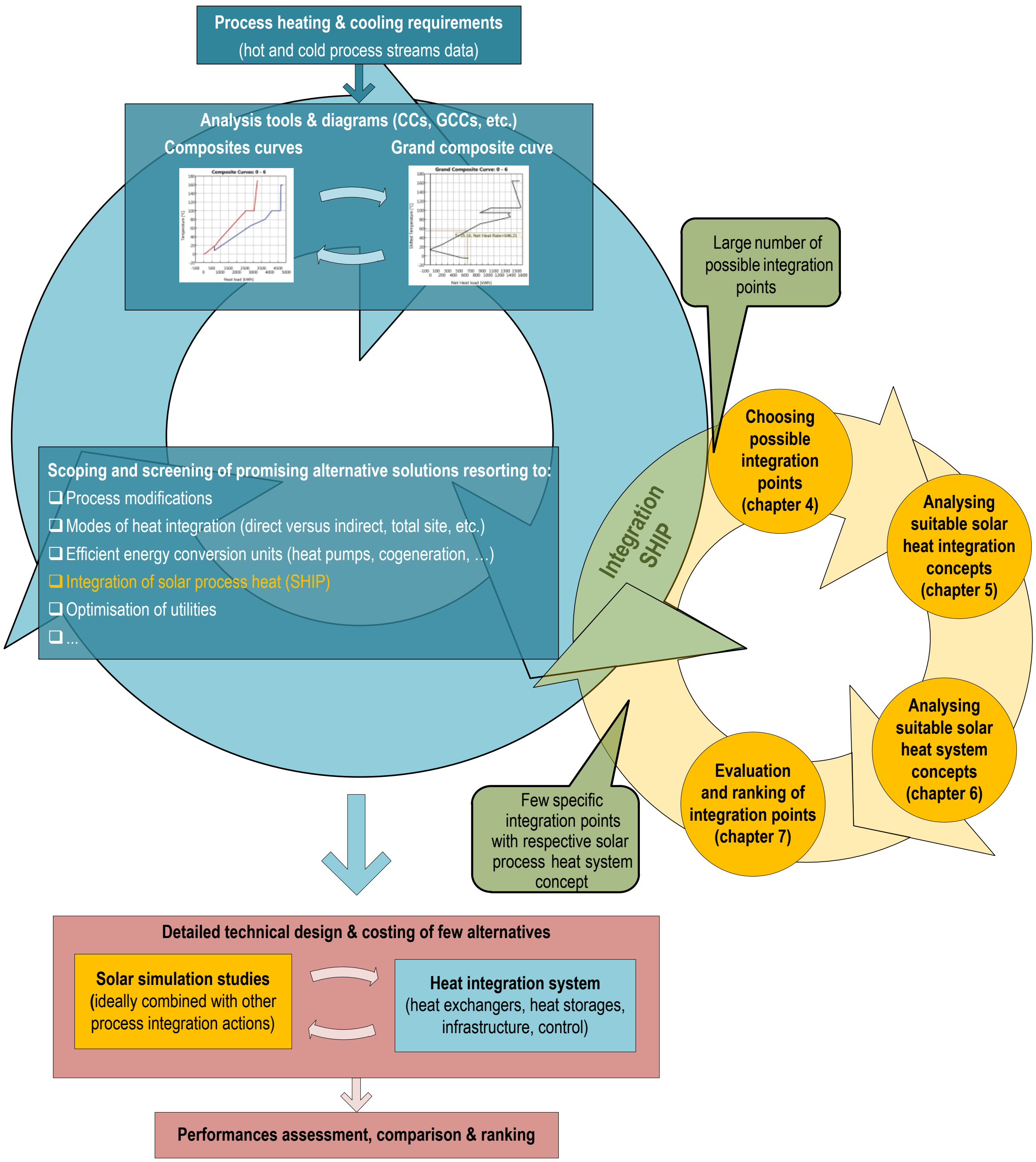


Figure 14: Simplified workflow of the Pinch Analysis based methodology extended to the integration of solar process heat (exemplified, for sake of simplicity, for process level integration).

3.1 PinCH

The PinCH software tool has been developed, and is being further extended, at the Lucerne University of Applied Sciences and Art, with the financial support of the Swiss Federal Office of Energy (OFEN/BFE) [23]. PinCH is a general purpose, Pinch Analysis based tool featuring a wide range of application. Batch processes and indirect heat integration with heat storage (fixed temperature-variable mass, as well as stratified storage types) may also be analyzed. Affordability, flexibility and ease of use are preferred to powerful optimization methodologies of other tools (e.g. no automatic design, no retrofit). PinCH is particularly suited for defining, managing and comparing different modes of heat integration for different operating cases (so-called energy target analysis to scope and screen most promising alternatives). A description of the methodological aspects and application examples may be found in [13]. PinCH includes the following specific tools and features (non-exhaustive list, some of the features are currently in development towards version 3.0):

- Spreadsheet based models (so-called e-modules) for quick heat & mass balancing of a selection of units operations, and the corresponding list of process streams;
- Fluid models (water, refrigerants, humid air) are available for fluid properties data;
- Common process stream table (may be imported from .csv file), available to define and analyze different processes;
- Close-to-reality process schedule definition, allowing daily, weekly, yearly schedule / production campaigns to be defined;
- Generation of repeated batch processes based on user-defined batch cycle duration;
- Energy targeting and simplification of multi-process integration problems and multiple operating cases;
- Decomposition of batch processes into time-slices and interactive simplification of batch processes to get a manageable number of relevant time slices for heat integration (see Figure 15);
- Assessment of intra-process and inter-process heat recovery potential (intermediate loops, heat storage);
- Conceptual design and fine tuning of indirect heat recovery loops with heat storage, based on Indirect Sources and Sinks Profiles (ISSP);
- Targeting result diagrams (user selected in a Filter Panel): composites curves (CC), grand composite curve (GCC), balanced curves (BCC, BGCC), split GCC, costs curves, Gantt charts (process level & stream level); utility, heat transfer area, and cost data. Time average model (TAM) & Time slice model (TSM);
- Sizing and setting of intermediate utilities, as well as energy conversion units (heat pump, mechanical and thermal recompression, internal combustion engine) against GCC;
- Interactively, user designed heat exchanger network (HEN), with supporting design tools: HEN grid & MER rules, split & isothermal merge of streams branches, driving force plot, HEX match specific sizing options (non counter-current, multi-pass, etc.) & cost functions. HEX summary table;
- Multiple base cases targeting and optimization, considering the re-use of heat exchanger area across base cases (or time slices).

Figure 15: PinCH: screenshot of the Energy Target Analysis interface for simplifying repeated batch processes to most energy relevant time slices for direct heat recovery.

3.2 SOCO

The SOCO software tool has been developed to bridge the gaps between classical Pinch Analysis and analyzing the true inter-linkage of heat recovery and solar heat integration in more details, taking into account time variability and heat storage simulation. The software, of which a detailed description has been published recently [21], allows Pinch Analysis for time-dependent streams and generation of heat exchanger and heat storage network considering variable heating and cooling requirements by an optimization algorithm, as well as corresponding flowsheet simulation.

Time variable process streams can be imported into the tool and the Pinch Analysis is carried out with time-averaged data, as well as for each time step (seconds, minutes, hours – depending on the user's definition). Via a scroll bar the changes of the CCs over time can be visualized. SOCO also includes an algorithm for proposing heat exchanger placement based on the theoretical potential shown in the composite curves. As all process streams can be variable, heat storages are suggested as well.

With such first information from the tool algorithms, the user can draw simplified flowsheets of the heat recovery measures and (if applicable) solar heat integration. In this case solar heat is included as hot stream in the stream database. The combined effect of heat integration through heat storages can then be analyzed in a simplified system simulation. The simulation analyses heat transfer in heat exchangers and storages, however does not include details of piping losses.

For working with SOCO on the food packaging line example process, it was assumed that the cooker and filler operate at 2 shifts Monday–Friday while the washer operates one shift every weekday. Assuming that the heat recovery potential can be tapped from all streams, all streams were kept in the analysis. The algorithm for proposing heat exchangers then suggests integrating hot product flow leaving the cooker with the incoming ingredients and including the heat generated by vapor condensation for the unit operation. In this way, the ingredients can be heated to about 72°C.

Some remaining heat of the cooking vapor is suggested for pre-heating the make-up water for the jars washer. Additionally, SOCO suggests using the heat of the filled jars to preheat this water flow. SOCO does not recommend heating the lye bath using heat recovery, as only the hot product leaving the cooker would be available in that temperature range, which is preferably for preheating the incoming ingredients. This is well explained by the criteria in the proposal generation of SOCO, which is – in addition to the user-defined settings of the importance of power, energy savings and exergy losses per HEX in the analysis – the similarity in heat capacity flowrate.

To evaluate the options in more detail, one can draw a simplified scheme of heat exchangers and storages in SOCO integrating a possible solar heat source as well. Let's assume vapor condensation cannot be realized for technical reasons. In that case, the integration of solar heat for preheating the ingredients (additional to heat recovery from the product leaving the cooker) would be possible, as well as heating the lye bath. Now, several considerations previously mentioned come into play: What supply and return temperatures are necessary for heating these unit operations? What is the effort of retrofitting the existing heat supply of the unit operations? Would an integration of solar heat into the existing supply line be technically and economically feasible?

It is assumed that the food packaging line is located in Europe, and it is recommended for an economic design of the solar plant, that both direct and diffuse radiation are used. In this case, a "low temperature collector" (non concentrating, glazed collector) should be chosen with the aim to integrate solar heat on the process level instead of integrating it into the existing steam line (as the process does not require direct steam, the make-up water heat demand is quite limited). The decision to integrate solar process heat for preheating the ingredients and for heat recovery from the hot product leaving the cooker is due to several reasons: 1) retrofitting an additional heat exchanger into the incoming line to the cooker is easy, and 2) return temperatures to the solar process heat plant can be kept low (e.g., below 60°C). This would not be possible if the lye bath is supplied by solar heat. A low return temperature and a considerable temperature difference between the supply and return are important for the efficiency of the solar system.

The interaction of the heat recovery measures and the solar integration in one central storage tank can be analyzed. SOCO allows drawing the concept in a simple flowsheet and running a system simulation after all storage and heat exchange parameters have been defined. The variability of temperature and heat flow over time is given for each stream via importing their data from Excel. For solar heat, the solar yields can be simulated in specific programs and imported to SOCO. After the system simulation, the visualization and export of heat storage stratification and heat exchanger performances over time is possible.

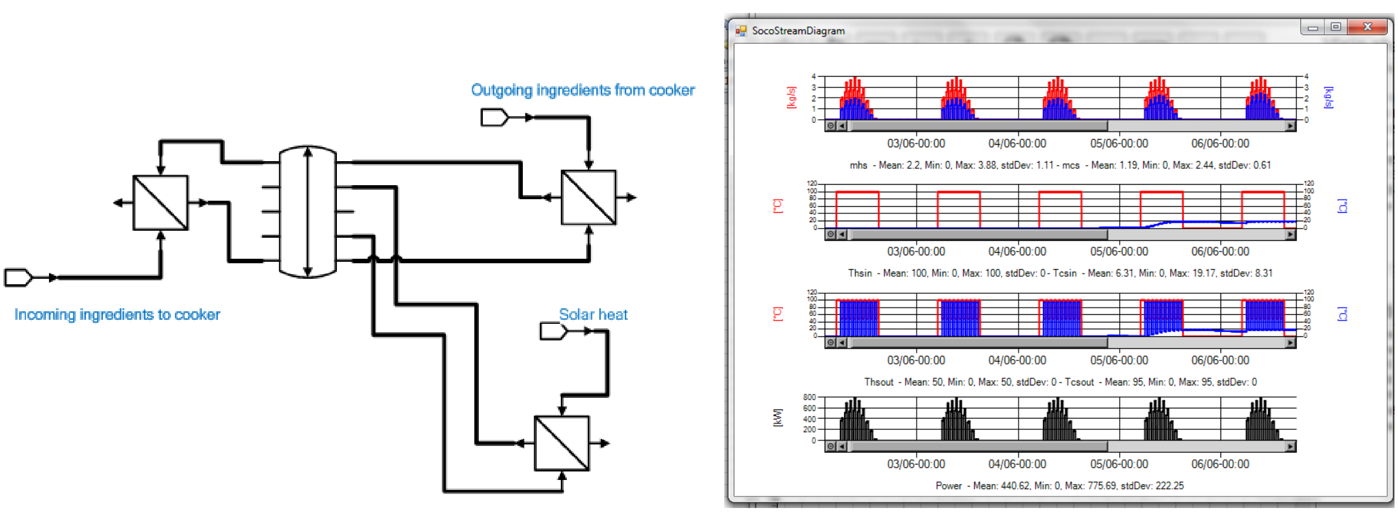


Figure 16: SOCO: flowsheet of the system simulation for combined heat integration and solar heat (left). Example of heat exchanger performance data visualization for the heat exchanger loading the heat storage with solar heat (right).

4 Conclusions & further work

Achieving the ambitious 80% reduction target of greenhouse gases emissions defined in the EU "Roadmap for moving to a competitive low carbon economy in 2050" requires both energy efficiency actions and substitution of fossil fuel by solar heat on a large scale. IEA SHC Task 49 aims at elaborating and improving methods and tools, and at collecting, preparing and disseminating key information to get prepared to take up this challenge. The Process Integration framework (and Pinch Analysis in particular) appears to be best suited for "simultaneously" addressing these two challenging issues in a systematic way and making sure that the solar process heat does not prevent other cost effective improvements (e.g., heat recovery, efficient energy conversion technologies, new process technologies) from being implemented. So far, the benefits and savings potential brought about by Pinch Analysis are often underestimated, especially in SMEs. Indeed, its efficiency and benefits go far beyond the usual trend of gaining a green image by "merely" adding a solar plant or resorting to good housekeeping and best practice actions only.

Framework conditions, technical constraints and degrees of freedom related to the solar plant make solar plant design a complex problem. In addition, the supply of solar heat must comply with essential rules of Pinch Analysis: solar heat must be supplied above the heat recovery pinch (i.e. at a temperature higher than the pinch temperature) and the solar heat rate up to a given temperature should not exceed the net heat deficit as defined by the grand composite curve (provided the process heat recovery is possible and cheaper than solar heat). The combination and/or competition of solar heat with other cost effective improvements increases the number of potentially attractive alternative solutions to be analyzed and compared. Pinch Analysis allows the scoping and screening of the most promising alternative solutions. However, the methodologies are primarily established for continuous processes in grassroots situations (i.e., new plant design), while the integration of solar heat requires time variability of heat flows and heat storage to be tackled, and essentially concerns retrofit projects (i.e., integration in an existing infrastructure). Although methodologies for batch processes and retrofit problems exist, few software tools (e.g., EINSTEIN, PinCH, SOCO, and OBI) provide the engineer with practical features for these issues and help with the heat storage placement and design. Despite attempts of these tools (especially PinCH and SOCO) further progress is needed, most notably in the following areas: 1) consideration of retrofit constraints in the determination of the possible alternatives and the placement of solar heat, 2) methodology developments for the supply level integration and total site integration of solar heat, and implementation of methodology into software tools, 3) analysis and design of variable heat flows and heat storage, and 4) computerization of assessment and comparison of alternative solutions to speed up and simplify their screening. An alternative to the present manual data exchange between process integration tools and solar simulation tools would be to introduce simplified models of solar collectors as a special hot utility and interfacing with meteorological data or to provide interfaces with solar simulation tools into Process Integration tools. These enhancements would improve the chances to bridge the gaps between solar plant design and process integration and get the most out the synergies of both fields.

ACKNOWLEDGMENT

Financial support from the Swiss Federal Office of Energy (OFEN/BFE) and the Austrian Ministry of Transport, Innovation and Technology (BMVIT/FFG) is gratefully acknowledged. The authors are also grateful to all the IEA SHC Task 49 participants for their willingness to exchange ideas and share expertise. Chapter 1.1 provided by Wolfgang Glatzl of AEE INTEC.

5 Literature references

[1] N. Pardo et al., Heat and cooling demand and market perspective, Joint Research Centre – Institute for Energy and Transport. European Comission, EUR -Scientific and Technical Research series (2012). ISBN 978-92-79-25310-2, doi: 10.2790/56532.
[2] European Commission, http://ec.europa.eu/clima/policies/roadmap/index_en.htm, accessed on June 26, 2014
[3] Pinch Analysis: for the Efficient Use of Energy, Water & Hydrogen, CANMET, Canada, 2003 http://www.nrcan.gc.ca/energy/efficiency/industry/processes/systems-optimization/process-integration/pinch-analysis/5521, accessed on June 26, 2014
[4] B. Linnhoff, Pinch Analysis – A State-of-the-Art Overview, Trans IChemE, Vol 71, Part A, September 1993
[5] B. Muster-Slawitsch et al., Integration Guideline, deliverable of IEA SHC Task 49 “Solar Process Heat for Production and Advanced Applications” (2015).
[6] H. Schnitzer et al., Minimizing greenhouse gas emissions through the application of solar thermal energy in industrial processes, Journal of Cleaner Production 15, 1271-1286 (2007)
[7] C. Brunner et al., Industrial Process Indicators and Heat Integration in Industries, International Energy Agency, IEA Task 33, J. Research, Graz, Austria, 2008
[8] S. Hess, O. Axel, Solar Process Heat Generation: Guide to Solar Thermal System Design for Selected Industrial Processes, SO-PRO Project, O.Ö. Energiesparverband, Linz, Austria, 2012
[9] H. Schweiger et al., Guide for EINSTEIN thermal energy audits, Barcelona, Spain, 2012
[10] J.J. Klemes (Editor), Handbook of Process Integration (PI) – Minimisation of Energy and Water Use, Waste and Emissions, WPE 61, Woodhead Publishing Limited, ISBN 978-0-85709-593-0, 2013
[11] S. Perry et al., Integrating waste and renewable energy to reduce the carbon footprint of locally integrated energy sectors, Energy 33 (2008), pp. 1489-1497
[12] P.S. Varbanov, J.J. Klemes, Integration and management of renewables into Total Sites with variable supply and demand, Computers & Chemical Engineering 35 (2011), pp. 1815-1826
[13] F. Brunner et al., Einführung in die energetische Prozessintegration mit der Pinch-Methode - Handbuch für die Analyse von kontinuierlichen Prozessen und Batch-Prozessen (in german), Bundesamt für Energie, Bern - Switzerland, 2014 (to be published)
[14] M.R.W. Walmsley et al., Integration of Soalr Heating into Heat Recovery Loops using Constant and Variable Temperature Storage, Chemical Engineering Transactions, Vol. 35, 2013
[15] B. Schmitt, Integration of solar heating plants for supply of process heat in industrial companies (in german), PhD Thesis at University of Kassel, Shaker Verlag, Aachen, 2014
[16] R.W. Clayton, Cost reductions in a Creamery identified by a Process Integration study at Express Foods Group, Energy Technology Support Unit (ETSU), Report RD/22/29, September 1987 (available from British Library Document Supply Service, bldss.bl.uk)
[17] F. Maréchal, Chapter 3.19.1.8, UNESCO encyclopaedia of life support systems, In: Frangopoulos Ch. And Tsatsaronis G., EOLSS Publishers Co Ltd, Oxford, UK, 2008
[18] I.C. Kemp, Pinch Analysis and Process Integration - A User Guide on Process Integration for the Efficient Use of Energy, Butterworth Heinemann, 2006, pp. 257-287
[19] B. Linnhoff et al., Process integration of batch processes, IChemE Symposium Series, Nr. 109, pp.221-237, 1988
[20] K.C. Furman, N.V. Sahinidis, A Critical Review and Annotated Bibliography for Heat Exchanger Network Synthesis in the 20th Century, Ind. Eng. Chem. Res., 2002, 41 (10), pp. 2335–2370
[21] B. Muster-Slawitsch et al., Application of an advanced Pinch Methodology for the food and drink production, WIREs Energy Environment **3**, 2014.
[22] I. Bulatov, Software Tools for the Heat Integration, in: J.J. Klemes (Editor), Handbook of Process Integration (PI) – Minimisation of Energy and Water Use, Waste and Emissions, WPE 61, Woodhead Publishing Limited, ISBN 978-0-85709-593-0, 2013, pp. 1059-1085
[23] Hochschule Luzern Technik & Architektur, PinCH website: http://pinch-analyse.ch/index.php/en/, accessed on June 26, 2014