IEA SHC Task 49

SolarPACES Annex IV

Solar Process Heat for Production and Advanced Applications

Potential Enhancement of Solar Process Heat by Emerging Technologies

Deliverable B 5

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1 IEA Solar Heating and Cooling Programme

The Solar Heating and Cooling Technology Collaboration Programme was founded in 1977 as one of the first multilateral technology initiatives ("Implementing Agreements") of the International Energy Agency. Its mission is *"to enhance collective knowledge and application of solar heating and cooling through international collaboration to reach the goal set in the vision of solar thermal energy meeting 50% of low temperature heating and cooling demand by 2050.*

The members of the IEA SHC collaborate on projects (referred to as "Tasks") in the field of research, development, demonstration (RD&D), and test methods for solar thermal energy and solar buildings.

A total of 57 such projects have been initiated, 47 of which have been completed. Research topics include:

- Solar Space Heating and Water Heating (Tasks 14, 19, 26, 44, 54)
- Solar Cooling (Tasks 25, 38, 48, 53)
- Solar Heat or Industrial or Agricultural Processes (Tasks 29, 33, 49)
- Solar District Heating (Tasks 7, 45, 55)
- Solar Buildings/Architecture/Urban Planning (Tasks 8, 11, 12, 13, 20, 22, 23, 28, 37, 40, 41, 47, 51, 52, 56)
- Solar Thermal & PV (Tasks 16, 35)
- Daylighting/Lighting (Tasks 21, 31, 50)
- Materials/Components for Solar Heating and Cooling (Tasks 2, 3, 6, 10, 18, 27, 39)
- Standards, Certification, and Test Methods (Tasks 14, 24, 34, 43, 57)
- Resource Assessment (Tasks 1, 4, 5, 9, 17, 36, 46)
- Storage of Solar Heat (Tasks 7, 32, 42)

In addition to the project work, there are special activities:

- SHC International Conference on Solar Heating and Cooling for Buildings and Industry
- Solar Heat Worldwide – annual statistics publication
- Memorandum of Understanding – working agreement with solar thermal trade organizations
- Workshops and seminars

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2 Introduction

2.1 Solar process heat

The large global share of total industrial heat demand of the total energy consumption, namely 24.4%, shows the importance of thermal energy supply in industry. A significant share of this demand is required below 250 °C (e.g. amounting to 31% for Germany, of which 2/3rd below 100°C [3]). Renewable heat supply has increased worldwide in the past years (with growth rates of 9% in 2013). For the temperature range below 250 °C solar thermal energy is a promising alternative energy source for industry. Based on the existing process technologies the potential of solar process heat has been calculated to 70 TWh in EU25 [4], while more recent studies resulted in a potential of 16 TWh/y for Germany alone. Despite this huge potential only a rather small number of process heat plants have been identified so far. Costs and flexibility of the solar thermal system often do not meet the expectations of industrial customers and suitable space is often a limiting factor. Within IEA Task 49/IV (http://task49.iea-shc.org/) a database has been set up recently that collects existing solar process heat plants. This "Solar Heat for Industrial Processes – SHIP" database gives a worldwide overview on existing solar thermal plants including information about e.g. the size of the collector field, collector technology or integration point in the production process. Until June 2014, 132 plants corresponding to a collector area of 136,500 m² have been reported in the database. Plant sizes vary from very small to very large – while the 52 smallest plants have a total collector area of 2,250 m² the largest 17 plants cover an area of 98,700 m². The largest number of plants have been reported in Europe (>60%), followed by Asia, the United States and Africa. The collector types used in the plants are diverse including flat plate collectors (about 50% of the reported plants), evacuated tube collectors, air collectors, parabolic troughs and Fresnel collectors.

2.2 The impact on the industrial process layout on sustainable energy supply

In its strive towards green, safe and efficient production processes, industry is starting to change its traditional practices. In engineering research, the aimed changes have been even called "re-industrialization" towards a green and safe economy. The ongoing developments can be seen in the following fields:
Emerging technologies – chemical and process engineering research is dedicated towards new technologies with highest process efficiency, ideally at low costs and at lowest possible material input. "Produce much more with much less" has been set as paradigma by the researchers active in process intensification.
Biobased industry developments – the biobased industry is a sector with growing importance with more and mopre products being develped based on biobased raw materials. This sector requires new technological solutions to render biobased products, be it bio-energy or other materials, competitive.

Obviously changes of the industrial processes will affect the energy supply strategies of companies. Some of the upcoming technologies rely on electricity as energy supply, such as microwave, ultrasound or plasma technologies, so there might be a shift towards more electrically driven processes. However, emerging technologies can act on several levels to reach a more sustainable energy supply:

- ⇨ by increasing process efficiencies the energy requirement is lowered;
- ⇨ by changing driving forces the required energy form may change; and finally
- ⇨ by enabling new efficient conversion technologies new energy sources (e.g. hydrogen production in fuel cells) can be tapped.

Within IEA Task 49, Subtask B is focussing on the integration possibilities of solar heat in industrial processes. In this context, also the questions are tackeled:
Which new technologies can stimulate the use of renewable (solar) heat?
Which technologies must be developed for reacting best on the hybrid energy supply in future?

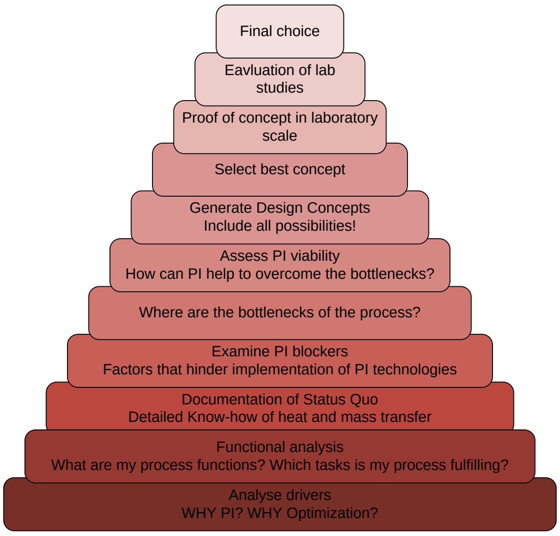
For the latter question, there are two main research strategies that tackle the technical bottlenecks of existing processes:

- ⇨ Adapt processes to become more efficient and better suitable for solar process heat
- ⇨ develop „solar process technologies“ as process technologies that are based on the use of solar light and heat.

To reach these future targets close cooperation between process engineers and energy experts will be necessary. Intensification strategies with effects on solar heat supply have been summarized by Muster and Brunner [1].

2.2.1 Engineering intensified process systems for renewable energy integration

The process engineering methodology to design an "intensified process" has been defined by various authors. Figure 1 shows the basic steps according to Reay, 2013 [2, 3]. The key to develop new processing solutions lies in the idenfification of the core process functions and the current bottlenecks that avoid the ideal realisation of these functions.



The basic step prior to this analysis is however "analyse the drivers". This means that it must be clear from the beginning what is the ultimate goal of the intensification approach. This might be an increase in process safety, an increase in process efficiencies, but it might also be the most economic integration of renewable energy, or a combination of these.

When the integration of renewable energy is one of the goals, it immediately becomes necessary not only to consider one specific process, but all processes along the production chain including the current energy supply technologies. The step "generating design concepts" then needs to be expanded to "analysing effects on overal energy management" (Figure 2). This means, that the view of the overall production system is important and the interaction between the processes must be analysed [1].

Figure 1: The PI tower - steps towards an intensified process (Muster-Slawitsch, 2014)

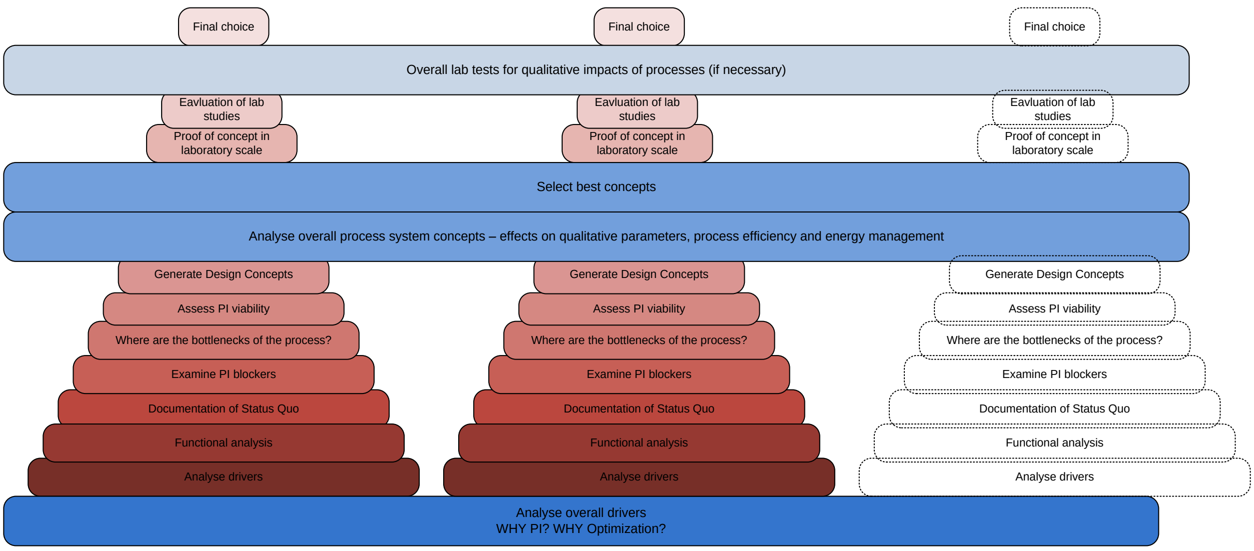


Figure 2: The PI tower for sustainable process systems (Muster-Slawitsch, 2014)

There is currently a strong trend towards hybrid energy supply where industry is seen as one player within large supply grids of heat and electricity. This changing energy supply will have an influence on the choice of process technologies, as PI and emerging technologies will have to be able to react on the variable offers. In such grids also exergy efficiency will be decisive to effectively re-use low grade waste heat or solar heat.

3 Intensification strategies with impact on solar heat supply

New process technologies aim to enhance heat and mass transfer to "intensify" reactions, mixing or heating/cooling of process media. These intensification strategies can be active, by actively introducing a new force, such as pulsation or radiation, or passive, by solely enhancing the transfer environment, such as extended surfaces for heat exchange [2]. In the following a few strategies used in new technologies are discussed with their impacts on solar heat supply.

3.1 Heat transfer enhancement

Generally, there are several strategies to increase of the heat transfer rate or overcome heat transfer limitations [1], such as:

- increase of temperature gradients,
- increase of heat transfer area,
- increase of heat transfer coefficient , or
- change to energy supply without thermal gradients

The increase of temperature gradients in heat transfer may happen over increasing the energy supply temperature or lowering the process temperature. For solar heat supply with non-concentrating collectors, the latter strategy is important: The lower the process temperature, the higher the efficiency of the solar plant. Ongoing developments in lowering required process temperature can be found in the textile industry and galvanizing industry due to the use of enhanced chemicals.

In heat transfer the required temperature gradients between energy supply temperature and process temperature can be lowered over increasing heat transfer areas. For solar heat supply this can be important in system concepts with non-concentrating systems, when existing heat transfer areas are not enough or make it difficult to realise low temperature heat supply. Intensified equipment will feature a high specific area of heat exchanger per volume. This is realised in compact heat exchangers, but may also be realised by adding additional heat transfer area in process vessel. An example is given below of introducing additional heating surfaces in mashing vessels.

Obviously heat transfer can be also enhanced via higher heat transfer coefficients, linked to the flow regime of the process media and the surface structure of the heat transfer surface. It is important to note however that in equipment with very high heat transfer coefficients, the temperature difference between energy supply temperature and return temperature is often very small. For solar heat supply, a reasonable temperature difference between energy supply and return temperature is important for the collector efficiency. In this sense, the heating profile of the process and depending on that the possible flow mode of the solar system (high flow vs. low flow) is important.

Another strategy in intensification is to change to energy supply without thermal gradients, in order to eliminate heat losses and to bring the energy to the point where it is needed. This may happen in microwave pasteurization where only the product is pasteurized without the needs to heat the pack. Microwave

heating naturally does not boost the potential for solar heat. However, direct solar radiation is a very important example for non-convective energy supply. Solar furnaces for melting or thermo-chemical reactions are an important research topic, mainly under the Solar Paces Programme of the IEA. Examples will be given below.
Additional, direct steam injection is a strategy relevant for concentrating systems. This becomes currently interesting for oil recovery plants where large plants are being built for solar steam production. One reference project is the 1021 MW Miraah project by Glasspoint in Oman (http://www.glasspoint.com/miraah/).

Solar collectors and reactions in synergy

As mentioned, an aspect linked to the heat transfer enhancement is the elimination of heat transfer from the solar collector to the process. This is realised in thermo-chemical reactions with solar furnaces, but may also be realised for non-concentrating collectors, coupling the reactor with the solar thermal collector. So far, such concepts have not been realised.

3.2 Batch to continuous

Batch processes operated in stirred tanks are per se not the ideal of an intensified process, as the flow of the process media is not structured and hardly controllable. Batch processes in this context describe processes in which batches are operated 2-3 hours in one vessel, after which the vessel is emptied and again refilled. Continuous processes become more efficient due to better process controllability, a reduction in operation time (via a possible increase in process rates), due to avoidance of unwanted by-products and unnecessary energy losses [4] [5].
The general advantages of a continuous process can be summarized as follows:

- High process efficiency, small residence time distribution, structured processes
- Good process controllability
- Low energy intensity (no peaks in heating/cooling demand)
- Low cleaning requirements
- Flexible processes
- Decreased energy distribution losses due to continuous heat demand
- Increased safety due to less storage of hazardous chemicals

As continuous processes decrease energy intensities due to a constant heating profile, they also make it easier to design a solar heating system. In batch processes it is necessary to design the solar heating system and all components (heat exchanger, storages) for rather large heat loads when the whole mass of one batch process must be heated at a certain time. When the same quantity of product is produced continuously the heat load is much smaller and the design of new energy supply systems, such as solar heat, becomes more economic.

3.3 Increasing the selectivity in separation processes

Increasing the selectivity in separation processes enables a more targeted operation of the separation process towards the required product component. Membrane processes increase selectivity and efficiency in transporting specific components and can thus improve the performance of reaction (e.g. by shifting the equilibrium of a certain reaction). Due to these facts membrane processes may intensify energy intensive techniques [6]. This intensification of transport and reaction efficiency may enable lower process temperatures, which can be exemplatory shown for membrane distillation or pervaporation. In this context, membrane processes may increase the potential for solar heat supply.

3.4 Intensification by electrohydrodynamics

Photochemistry was used for the production of fine chemicals since the early 1900s. Especially for the production of fine chemicals a few processes are used in chemical industry since then. However a wider market introduction was hindered by two main factors, the principle concerns of the traditionally thermochemical based industry and the cost of the necessary light sources. The second point is especially relevant as industrially mainly mercury lamps are used which not only produce light but also substantial heat that has to be removed. Using solar radiation in the UV-A and visible light range therefore has the advantages not to heat up the solution as much as the artificial light sources, therefore reduce the cost for cooling, for power, and for the recycling of the lamps. It could be shown even in very compact plants that some 10 m^2 of solar photo-reactors even set-up in a not favorable location can provide fine chemicals in the single digit percentage range of the annual world production. An additional benefit of such solar chemical production would be the marketing as it is an obviously very clean way to produce substances like fragrances. Even bulk chemicals could be produced like the precursor of polyamides like Nylon® cyclohexanone-oxime.

It benefit is also that light can drastically improve the selectivity of industrially relevant chemical reactions e.g. for

- ⇨ Waste water treatment (see 3.3)
  - Semiconductor photocatalysis
  - Fenton reaction
- ⇨ Chemical reactions
  - selectivity of toluene oxidation to benzaldehyde
  - cyclohexane oxidation to cyclohexanone

4 Examples of new technologies (potentially) driven by solar heat

In the following a few selected examples of technologies driven by solar heat are discussed that feature new reactor concepts or combine upcoming technologies with solar process heat. While some are available in pilot scale or even industrial scale, others have only been tested in lab scale or estimated within potential studies.

4.1 *Extended heat exchange surfaces in stirred tanks*

When retrofitting steam heated stirred tanks to low temperature solar heat supply, the existing heat transfer area may be limiting. In Austria, a solar heated mashing process has been realised in the Brewery Göss. To enable heat supply at lower temperatures new heating plates were inserted in the mash tun. These additional heat exchanger surfaces allow the mashing process to be operated at supply temperatures around 95°C. 1500 m² solar collector area has been installed to operate the system. District heating from a local biomass plant serves as back-up heating system.

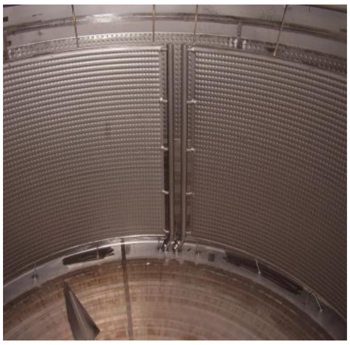


Figure 3: Additional heat exchange plates (GEA Brewery Systems)

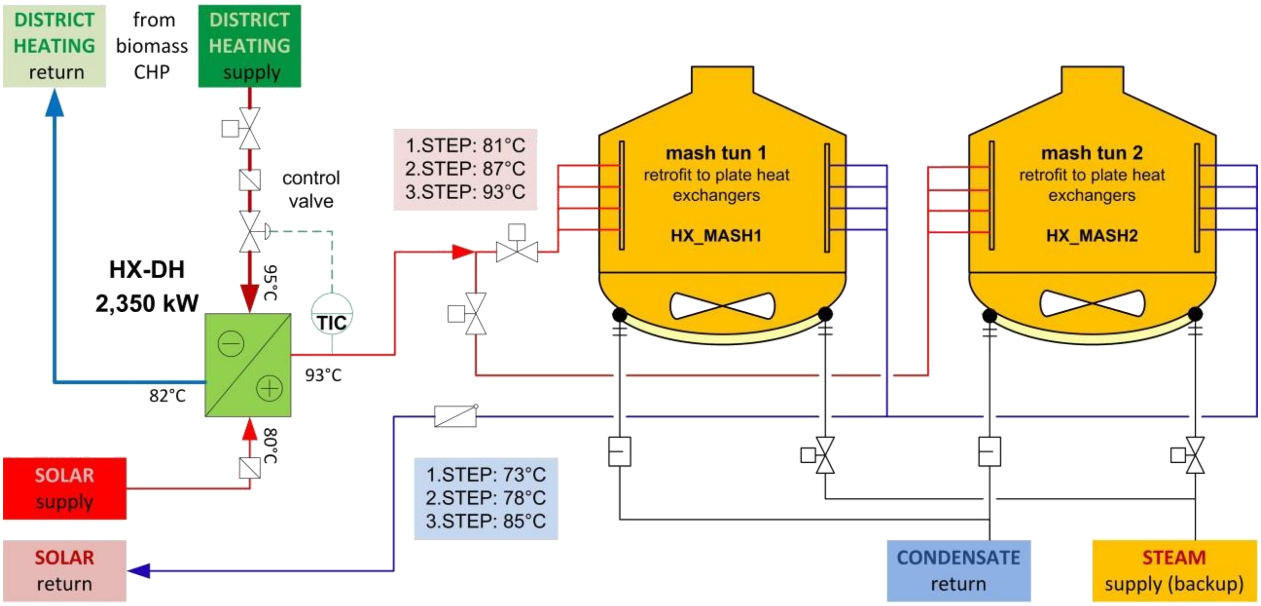


Figure 4: Solar heated mash tuns – integration concept (AEE INTEC)

4.2 Membrane technologies

4.2.1 Membrane distillation for new applications

Membrane Distillation (MD) is an emerging thermal separation technology [6]. The driving force of the process is the vapour pressure difference triggered by a temperature difference across the micro porous membrane. The selectivity of the MD is established due to the impermeability of the feed liquid through the hydrophobic membrane and the respectively permeability of volatile compounds through the pores of the membrane. MD is a promising separation and purification technology since it is a thermally driven, cost effective process with high product quality. The fact that MD can be operated at low temperature levels enables the integration of solar thermal or waste heat as energy source. However there are still barriers needed to be overcome such as the, compared to RO, lower permeate flux due to concentration and temperature polarisation effects, as well as the relatively high heat loss by conduction [7].

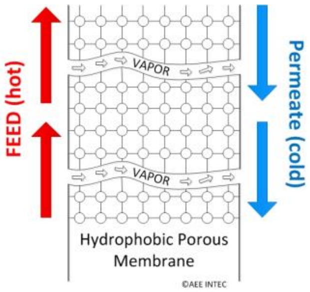


Figure 5: Process schematic of membrane distillation

Solar thermal energy could be used in membrane distillation to preheat the feed solution prior to entering the membrane module. In such designs the collectors can operate at target temperatures close to (or even below in case of preheating only) the process temperatures. A possible process scheme has been shown in [1].

Basically the MD process can be applied to any separation challenge as far as the membrane is suitable (thus non-wetting) in the respective process liquid. The classic application is the extraction of distilled water from a feed solution with non-volatile components. Currently there are many applications of Membrane Distillation in solar desalination, where stand-alone plants can supply distilled water in decentralized areas. More and more focus is being put on the extraction or concentration of highly valuable components as well as on the treatment of waste water, industrial water or for any other kind of decontamination application with liquid eduts.

Membrane Distillation provides the big advantage of being a thermal driven separation technology, with can be driven at relatively low temperature levels compared to normal evaporation. This offers perfect conditions for the application of solar thermal or waste heat. Additionally and most important, it opens the pathway for completely new energy concepts, specifically in combination with waste water treatment.

4.2.2 Pervaporation

Pervaporation is also a relatively new membrane based separation process. In contrast to membrane distillation, a selective membrane is used in pervaporation and separation is based on selective solution and diffusion of the permeating components in the membrane. Consequently, physical-chemical interactions between the membrane material and the permeating molecules play a crucial role for separation. This renders membrane selection and optimization of operating conditions a challenging task which still needs extensive experimental support.

Because of the nature of the driving force pervaporation is not limited by vapor-liquid equilibria. Consequently, main fields of applications are applications where conventional technologies are energy demanding or reach their limits such as the separation of azeotropic or close boiling mixtures. Separation of heat sensitive substances is another potential application as pervaporation may operate at lower process temperatures than, for instance, distillation. This is not only beneficial for heat sensitive components but may also help suppress unwanted side reactions in reactive mixtures. Ether formation

during esterification reactions is a prominent example thereof [8]. Water removal when performing the esterification in a membrane reactor shifts the equilibrium to the products' side and allows for full conversion of the reactants.
Direct application of pervaporation for key separation steps in chemical industry or combination with classical technologies either in series or as a hybrid approach are promising.
Selective evaporation of the permeating components in pervaporation has a positive effect on total energy consumption for the separation step. Lower operation temperatures compared to distillative separation result in reduced energy costs and give access to integration of low temperature heat. Pervaporation-assisted methyl acetate synthesis via esterification of acetic acid with methanol, for instance, could be performed well below boiling point (e.g. 40-50°C). This renders integration of low temperature solar thermal heat predestined.

4.3 Oscillatory baffled reactors

Oscillatory baffled reactors (OBR) have been researched by numerous researchers in the past years mainly for chemical applications. A core characteristic of OBRs is their ability to decouple flow velocity and residence time. This is achieved via oscillations inducing turbulent flow of process media (typically Re 1000-2000) between baffles while the net flow velocity remains in the laminar regime (Re 50-200). Oscillating reactors are thus perfectly suited for processes in which long residence times are necessary and high mixing performance is essential. Oscillations are induced into the fluid via a piston, the reactor itself remains stationary. The area between the baffles is highly turbulent and ideally mixed. Very high mass and heat transfer coefficients can be reached in this way [9, 10].
A number of studies [11-17] prove that the implementation of OBRs can lead to a significant improvement potential in chemical processing with increase in productivity of 30-40%, shortening of reaction times of 50-90 % and an increase of heat transfer up to a factor of 4. Due to increasing heat transfer coefficients in comparison to stirred tanks, they enable low temperature heat supply and theoretically enable a better integration of solar process heat [1].

4.4 Solar water treatment

Treatment of water by solar energy is normally not based on thermal but on the photon driven processes. However, also thermal treatment might be an interesting application in the future. It would merge water treatment with desalination technologies.
Nevertheless the solar water treatment technologies developed are interesting in this framework as they use a substantial amount of energy comparable with large flat plate or vacuum tube collectors for thermal processes. A number of solar water treatment demonstration have been carried out over the last nearly 20 years[18] dealing with different waste waters from air washers of automotive paint spay lines to the degradation of crop protecting agents or contaminants from rocket fuels [19]. It could be shown that cost reduction up to 80% compared to the state of the art can be achieved. However additional activities are necessary to overcome market introduction barriers [20].

4.5 Solar furnaces

4.5.1 Solar glass melting

Most glass is produced from a mixture of 71–75% silica sand, 12–16% soda ash and 10-15% limestone (*soda-lime-silica batch*), fed into a tank furnace at $T_m \approx 1500^oC$, causing decomposition of the carbonates to oxides and their dissolution into a melt pool (*melting*) which is then held at T_m to maintain sufficient fluidity for homogenisation and degassing (*fining*). The fined melt is then cooled to 1100-1300^{o}C before being output from the furnace to be formed into the desired article as it rapidly cools to the glass transition temperature ($T_g \approx 550^oC$). Finally, the glass article transferred to an annealing oven where it is held at T_g before being slow cooled to room temperature to relieve internal stresses.
Following a series of proof of concept experiments (Ahmad, Hand, & Wieckert, 2014), a new, direct solar receiver-reactor for glass melting has been tested, using a high flux solar simulator beam, to demonstrate the use of concentrated solar radiation to provide the primary process heat for the glass making process, with secondary electrical heating to provide control while dealing with intermittent solar radiation

availability. This *solar glass furnace* (Figure 6) consisted of an insulated box, with a 6cm-dia aperture in its roof, for pelletised soda-lime-silica batch and a concentrated solar beam inlet. Inside the insulated cavity there was a fused silica crucible (187 mm-id) surrounded by SiC electrical resistance heating elements, which served the following functions:

1) Enabled the melt and containing crucible to be held above 1000^{o}C during periods when direct solar radiation is not available, such at night or during cloud cover. Otherwise, if left to cool below this temperature, the crucible would fail due to crystallisation and thermal expansion mismatch between the crucible and contained glass;
2) Reduced and controlled the cooling rate of the furnace refractories which prevented thermal shock during period of sudden loss in solar radiation availability;
3) Enabled initial pre-heating of the glass and containing refractories to prevent thermal shock which could otherwise eventually result from the daily cycles of rapid heating associated with direct irradiation by the beam;

Glass was output from the furance through a drain in the base of the crucbile, which lead to an outlet tube, which passed through the bottom insulated wall of the furance via an independently controlled tube heater, coupled with a removable, heat dissipating steel plug at the end of the outlet tube, which together functioned as a freeze-thaw valve to control the outflow of glass.

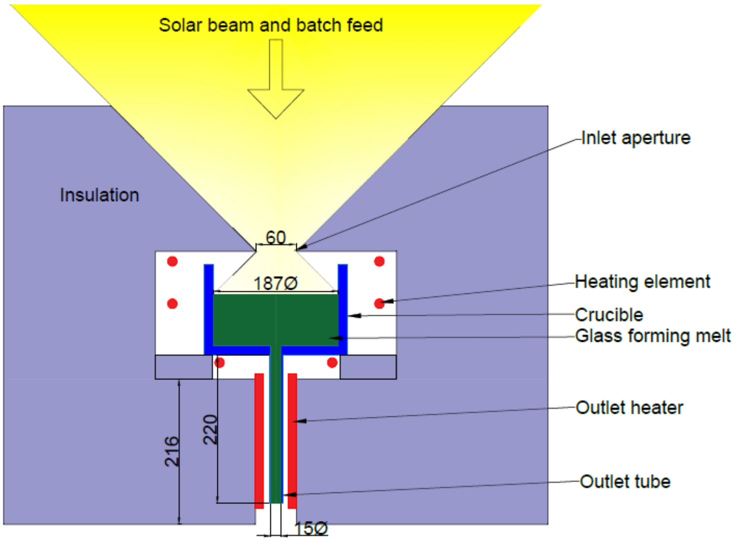


Figure 6 Schematic drawing showing key features of the solar glass furnace

With 5.25kW of radiative power delivered by the beam into this solar glass furnace, stable melting cycles were achieved, with charges of 300g soda-lime-silica batch requiring 15 minutes to melt, reactions to complete and the melt temperature to recover to sustain 1560oC. This corresponded to a thermal efficiency of 16%, based on the theoretical energy of 2.7KJ/g, which included the energy required to increase the temperature of the batch from room temperature to Tm and the chemical heat of reaction.. Then, the melt was held for an hour for fining which resulted in successful de-gassing and homogenisation. Finally, the melt was released from the outlet to demonstrate a forming process, whereby the glass was manually collected in a mould and pressed into a disk shaped pieces and transferred to a separate annealing oven.

These experiments successfully demonstrated a scalable glass making process with primary process heat provided by solar radiation with similar performance to that of comparable intermittently operated fossil fuel fired glass furnaces. However, since most glass is produced in much larger, continuously operated furnaces with stringent quality requirements, it is difficult to realistically envisage any significant fraction of the of the process heat used for commercial glass production to be substituted by solar heat within the near future. The most amenable types of glass production for solar heat integration are probably glass fibres for insulation wool and art glass production, due to their less stringent glass quality criteria compared to that of glass production for containers, windows and fibres for structural applications. In any case, solar glass melting will likely to be limited to locations with very high direct solar radiation availability and intensity.

4.5.2 Other applications of solar furnaces

Highly concentrated solar radiation can also be used for the recycling of light metals like aluminum or magnesium [21]. Even for industrial use such applications are often limited in side and operated in batches of up to a few tons. Therefore they fit perfectly to solar furnaces or similar designed small concentrator systems with an elevated receiver for a higher efficiency. As the recycled product can be used either directly for production or will be transported to a production plant in liquid or solid form the recycling process can be decoupled from the available solar radiation, improving its applicability. In the early 2000s it could be shown that in a solar heated rotary kiln even higher quality aluminum can be produced than in industrial ones as the material is only heated by radiation and therefore is not exposed to the off-gases from burners [22]. Presently demonstrations are prepared to show the applicability in promising solar locations with the additional goal to reduce the power load from the electricity grit. This is very often an economically important reason to invest in solar technology instead of setting up stronger power lines.

4.6 Solar particle technology for high temperature processes

High temperature energy for thermal processes is often supplied by expensive fuels such as heavy fuel oil or even electricity. Out of the different potential uses, the industry sectors which are considered most prospective, concerning fossil fuel or electricity substitution in high temperature processes (>400°C) are the non-metallic mineral industry, the iron and steel industry (eg. scrap pre-heating before a furnace), the non-ferrous metal industry (eg. aluminum recycling), the chemical industry and thermal enhanced oil recovery.

The use of solid particle receiver tower technology is a suitable technology for energy supply to high temperature processes [23, 24]. Solar radiation is concentrated by a two-axis sun tracking heliostat field and focussed on a receiver located in a tower as shown in Figure 7. Here particles directly absorb the incoming flux and are heated to up to 1000°C. The heated particles are then transferred by a vertical lift system to low cost high temperature storage. The energy can then be extracted on demand by a heat exchanger. The cool particles are then stored in a low temperature storage. The particles are then transported up the tower to be recirculated through the receiver and reheated. Air can be generated in a commercially available moving bed heat exchanger or steam can be generated in a particle steam generator. Alternatively steam can be generated via intermediate heat transfer from particles to air and the subsequent high temperature air integration into a conventional steam generator. The high temperature air can be utilised to directly replace combustion of fossil fuels or electricity used in thermal processes.

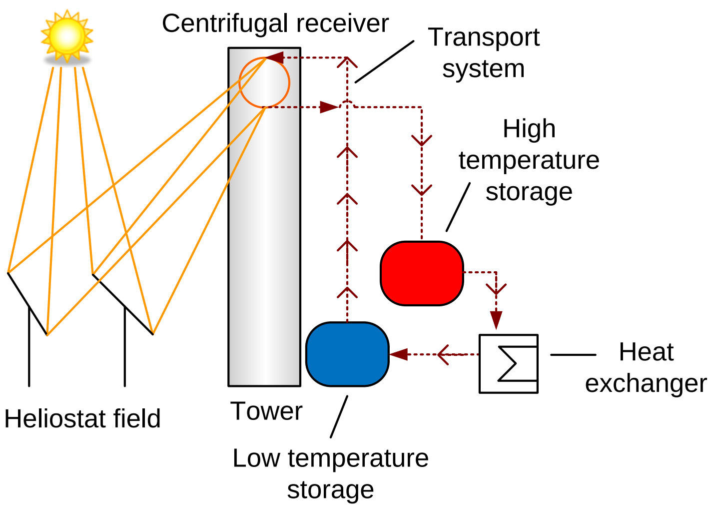


Figure 7: Operation of SPR solar system

High heat fluxes can be achieved, due to the direct absorption, allowing a compact receiver design, which yields together with the cavity design and low radiation and convective losses, resulting in high receiver efficiencies, even at high temperatures. Furthermore, no corrosion or freezing issues are present compared to the state-of-the-art CST storage fluid, i.e. molten salt. Due to the high temperatures a high storage density is achieved making transport of particles off site (e.g. via truck or special transport vehicles) feasible. This allows for a multiple tower solution enabling high solar field efficiencies and sequential installation. Furthermore hot particles from the solar towers can be transported to one or more heat consumers located in the vicinity of the particle receiver plant. A particle receiver solar tower plant can be installed in the vicinity, avoiding space constraints often existing next to the heat consumer (e.g. industrial plants) as well as air pollution and soiling issues caused by the industrial plant. Direct particle solar heat capture and heat storage can be achieved at commercially attractive cost, in particular at high operating temperatures, enabling a 24/7 solar heat supply for base load consumers which is usually the case in industry.

4.7 New storage technologies

New technologies that will stimulate the use of solar process heat are also new storage technologies. Sorption storage is one technology that is being researched as promising storage solution with low thermal losses. With sorption, the principle is that a vapour is taken up by the sorption storage material. This uptake releases heat, the discharging process. When charging the material, the vapour is driven out of the sorption material, thereby storing the thermal energy. Sorption can have high energy density, with materials like zeolite or silica gel as known solid sorption materials and sodium hydroxide as a known liquid sorption material. Water vapour is the other component for these sorption materials. The heat losses with thermochemical storage are very low (only the sensible part of the heat stored will be lost) and therefore this technology is very suited for long term storage.

At the moment, only few applications have been developed for solid sorption and are in the field test phase.

Solar thermal energy can be used to charge a solid sorption storage device, using for instance zeolite. Collector temperatures of about 150 °C are needed to dry (charge) the material. Latest results show that depending on the charging temperature energy densities up to 180 kWh/m^3 are possible [25]. The dried zeolite then can be used to dry (0,25 g of water vapour per g zeolite) and the heat generated to (pre)heat the material to be dried in the process. Laboratory facilities for researching zeolite storages as long-term solar storage have been set up by AEE INTEC, Austria in 2015. Once the applicability as long term heat storage is proven, sorption storages can be interesting for solar process heat projects, especially for increasing solar fractions by making more use of the sunshine hours in summer.

Sorption storage is extra attractive if the process in which the heat is needed also needs drying. The water vapour taken from the drying process can be used to drive the discharge of heat from the storage material.

5 Conclusions and Further research aspects

From the example aboves, we can see that emerging technologies can act in several ways on the potential for solar process heat. The combined enhancement of and mass transfer is most promising, e.g. when light/UV can have positive effect on reaction; or membrane processes enhance reaction efficiency and potential for solar. Additionally, any measure which lowers heat demand peaks will be beneficial. An important aspect is the change from batch to continuous processing. The sun will always remain a batch process itself, and the combination with a continuous load profile instead of another contradicting batch profile will increase the efficiency of the solar process heat system.

A number of future research questions may be tackled to see in which ways new technologies can boost the solar process heat potential.

New solutions for solar drying are one example. Drying is an energy intensive process usually at low temperatures. While there have various solutions proposed for solar drying with conventional flat plate collectors or air collectors, it seems to be important to re-visit this research topic with new solutions of “solar driers” maybe in conjunction with sorption storage. The importance is also underlined by numerous bio-based processes that often require a drying step with low energy intensity to render them economic.

The intensification strategy “synergy” between reactor and collector is another future research topic. The more precise solar heat can be used locally at the place of reaction, the lower will be heat losses to the environment. This is researched already for waste water treatment and in solar furnaces, however it might be interesting to tackle this research question also for collectors that may act as reactors at the same time.

Technologies that allow low temperature heat supply will be of core research interest to enable use low temperature heat supply, be it waste heat or solar. Here membrane distillation is a prominent example, combining positive effects in heat and mass transfer. Oscillatory baffled reactors as alternative to stirred tanks might be another niche application.

Finally, research on system analysis will stay important: which emerging technologies serve best to reach an economic energy supply based on renewables? In future available energy supply grids may have an impact on the choice of technologies in industry, so processes might have to be changed because of the local heating network. Modelling and designing of sustainable production sites will be important, where the effects of new process technologies on the overall energy management of the site can be analysed.

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