Roadmap for industrial solar heat supply in combination with emerging technologies

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Preface

This study has been carried out as part of the Sustainable Development master (track Energy and Materials) at Utrecht University. The research has been conducted over the last 6 months at the AEE-Institute for sustainable technologies and is part of the INSHIP (Integrating National Research Agendas on Solar Heat for Industrial Processes) project. A separate report regarding the potential of emerging technologies will be published within this project.

I would like to thank my supervisors Wina Crijns-Grauß and Christoph Brunner for their guidance and support during the research project. Furthermore, I would like to thank Bettina Muster-Slawitsch (AEE INTEC) and Petra Königshofer (AEE INTEC) for the many fruitful discussions and their engagement during my work at AEE INTEC.

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Executive summary

Currently, fossil fuels are the predominant fuel for heat generation in industrial processes. In order to reduce greenhouse gas emissions, a switch towards renewable alternatives has to be undertaken. Solar thermal heat poses a promising option; however, it has not been deployed widely. Emerging technologies could become a key element in addressing current barriers and facilitate solar integration in industrial processes. This study, therefore, analyses the potential coming from emerging technologies to enhance solar thermal process heat.

The methodology to answer the research aim was threefold. In a first step, renewable alternatives to conventional heat conversion technologies were explored. Moreover, current projects with solar integration were analyzed in order to identify barriers. This led to the second step: the creation of a framework for selecting promising technologies. This framework is based on three identified bottlenecks, namely low heat transfer coefficient, high-temperature demand and batch production. The selected technologies were then analyzed according to general parameters (costs, easiness of integrating the technology, efficiency, quality of the product, possibility of solar integration, development status and multiplicativity) to estimate the overall potential.

The results showed that there are several renewable alternatives to conventional heat conversion technologies, and solar thermal heat is really promising as it could cover low, medium and high-temperature heat demand. The identified barriers of current solar process heat projects mostly refer to costs, availability of solar irradiation and high-temperature demand. Furthermore, knowledge gaps, investment risks, and lack of policy support are obstacles. Technical challenges, such as the lack of technologies for a specific purpose were also mentioned. Based on the introduced framework 6 process technologies were selected: extended heat exchange surfaces, pervaporation, membrane distillation, oscillatory baffled reactors, pulse combustion drying and microchannel reactors. On a supply-side solar particle technology and solar furnaces were chosen. The outcome of the potential analysis proved these technologies, especially pervaporation, pulse combustion drying and microchannel reactors to be beneficial not only for solar integration but also with regard to other parameters such as efficiency, costs, and quality. Supply technologies lag a bit behind due to the lack of availability of high solar irradiation mainly in Northern Europe and the respective high costs. The selected technologies are therefore suitable for overcoming identified technical barriers and expanding the potential of solar process heat in the EU. However, policy support is needed to overcome non-technical issues such as costs and knowledge gaps.

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1. Introduction

1.1. Background

In 2016 the total final energy consumption reached 556 EJ worldwide (BP, 2017). The EIA (2017) estimates a rise in energy consumption of one-third until 2040. Taking the IPCC's goal of limiting the temperature increase to 2° C and further to 1.5° C into account, in order to significantly reduce the impacts of climate change, the mentioned numbers pose quite a challenge, as 78% of the total GHG emission from 2000 to 2010 are attributed to fossil fuel combustion and industrial processes (IPCC, 2014). This is especially critical as currently, fossil fuels are extremely significant in the worldwide fuel mix with 86% (BP, 2017). In the EU heating and cooling account for half of the total energy consumption and is mostly covered by fossil fuels (European Commission, 2016). This underlines the significance of focusing on heating and cooling alternatives in order to reduce GHG emissions. Especially industrial heat is currently a big consumer of the global energy demand with 24.4% and thus offers a great reduction potential (Muster-Slawitsch et al., 2016).

Taking a closer look at industrial processes reveals a wide variety of heterogeneous activities. Particularly, the temperature demand for industrial processes depends widely on the industrial sector itself and on the specific process (Figure 1) (Pardo et al., 2012). It is estimated that high-temperature (>400°C) processes account for 43%, medium–temperature (100°C-400°C) processes for 30% and low-temperature processes for 27% (<100°C) of the total process heat demand (Werner, 2006). Numerous industries even show that 60% of the total heat demand require a temperature below 250°C (Vannoni et al., 2008).

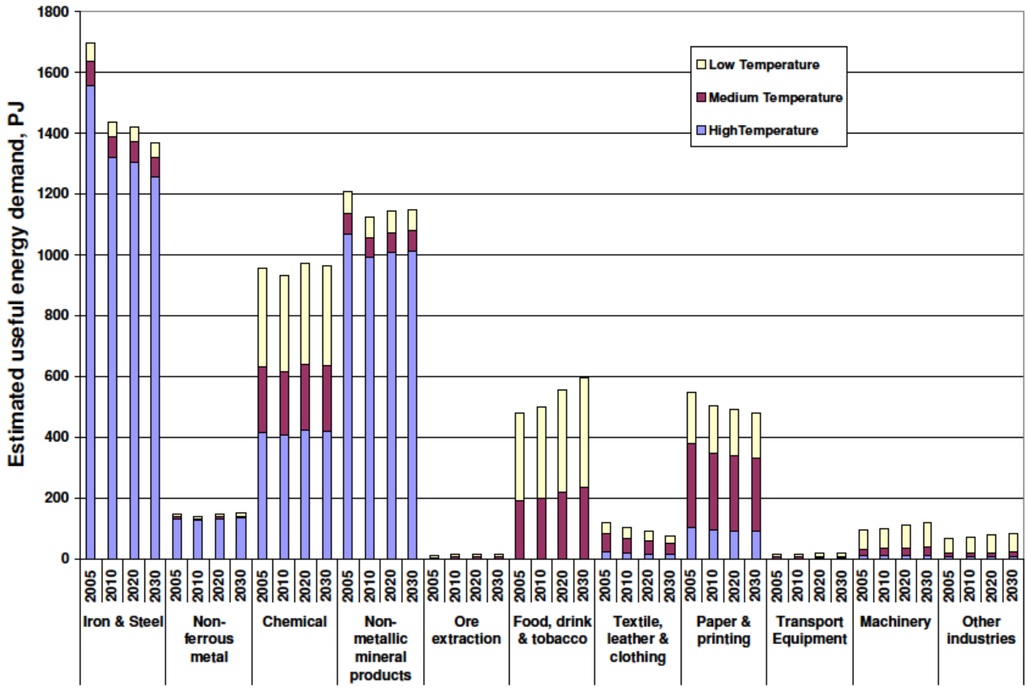


Figure 1 Estimated useful heat demand in the European industry (Pardo et al., 2012)

This is of high interest as industrial process heat driven by solar energy is expected to offer a vast potential for low and medium heat processes and could, therefore, reduce the dependency on fossil fuels (IEA, 2012). It is estimated that solar process heat could potentially generate 70 TWh in the EU 25 countries and could cover 3% to 4% of the industrial heat demand (Vannoni et al., 2008).

However, currently, only 126 MW_{th} for European countries have been reported within the SHIP plants database, where companies are asked to register their solar process heat projects (AEE INTEC, 2017).

This illustrates that currently barriers are in place, limiting the potential of solar process heat. It is of interested to assess whether emerging technologies (ET's) could pose an option in overcoming these barriers and therefore enhance solar heat integration in industrial processes.

1.2. Knowledge gap and research aim

On the one hand, several extremely promising emerging technologies have been identified such as membrane technologies, utilization of microwaves or cavity reactors (Caro & Noack, 2008; Cecilia et al., 2007; Deshmukh et al., 2007; Gogate, 2008; K. Kumar & Moholkar, 2007). These novel technologies aim at increasing the efficiency of processes exemplary by an increased mass or heat transfer. These advantages in comparison to the conventional process design are placed under the concept of process intensification (PI).

On the other hand, efforts have been undertaken in the field of solar integration in industrial processes. The IEA SHC project group has carried out research in the area of process heat collectors, where thermal enhancement strategies are addressed and available collectors presented (Horta, 2015). In addition, the technical-economic feasibility has been analyzed (Giovannetti & Horta, 2016). Furthermore, various studies have estimated the potential of solar process heat for specific industrial sectors (ESTIF, 2006; IRENA & IEA-ETSAP, 2015; Kalogirou, 2003; Sharma et al., 2017).

However, the link between emerging technologies and the resulting potential enhancement of solar integration in industrial processes has not yet been the focus of intensive research. One study explored the benefits of several PI strategies for solar integration (Muster & Brunner, 2015). Moreover, some promising emerging technologies for solar integration have been introduced (Muster-Slawitsch et al., 2016). However, no overarching analysis of emerging technologies enhancing solar integration has been conducted. This research analyzes current implementation barriers for solar integration in industrial processes and explores the possibilities emerging technologies hold in order to overcome those limitations. The scope of this analysis is EU-wide. Bearing this goal in mind the following research question is asked:

To what extent can emerging technologies expand the potential of solar process heat in the EU?

In order to satisfactorily answer the research question a set of 5 sub-questions has been developed:

1. What are alternatives to substitute fossil fuels with renewable energy sources in conventional heat conversion technologies?
2. Which characteristics regarding sector, location, and temperature range can be identified in current projects with solar heat integration and which barriers pose limitations?
3. Which ET's could play a key role in overcoming the identified limitations in order to increase the potential of solar process heat?
4. How do the specific characteristics of ET's relate to the potential for solar integration in industrial processes?
    a. Which are the application areas of ET's?
    b. Which are issues ET's are currently dealing with?

    c. In what way do ET's address current barriers to solar integration in industrial processes?
5. How can the potential of different technologies be evaluated?
    a. Which criteria have to be considered for the estimation of the overall potential?
    b. How can the influence of each criterion on the overall potential be identified?

Sub-question 1 analyzes the possibilities of current energy conversion technologies to be driven by renewable energy sources. Such a transition might be performed easier than the one to emerging technologies, as the required technology is already in place and is therefore explored beforehand. Sub-question 2 gives an overview of currently implemented industrial solar process heat projects. An analysis of these projects gives information about the characteristics and main barriers of the installations. In sub-question 3 emerging technologies are examined according to the possibility to overcome the identified barriers. The general characteristics of these technologies are then further explored in the next sub-question. The results of sub-question 4 are of interest in sub-question 5, where criteria which are influential on the overall potential are selected and weighted. The findings of the sub-questions will answer the main research question.

2. Theoretical background

This section describes the most important concepts used in this paper. Common nomenclature and definitions regarding process intensification, emerging technologies, industrial process heat, and potential analysis are presented. The research is embedded in the creation of a roadmap, for which such a framework is introduced.

2.1. Process intensification

Process intensification (PI) is defined by Creative Energy (2008) as “a set of often radically innovative principles (“paradigm shift”) in process and equipment design, which can bring significant benefits in terms of process and chain efficiency, capital and operating expenses, quality, wastes, process safety, and more”. Reay (2007) defines process intensification as ‘‘Any engineering development that leads to a substantially smaller, cleaner, safer and more energy-efficient technology”.

The main attributes of process intensification can be summarized the following way:

- Combination of functions, leading to a smaller plant size;
- Overcoming heat/mass transfer limitations entailing faster/more efficient processes;
- Higher controllability through a switch from batch to continuous production (Muster-Slawitsch, 2014).

Therefore, process intensification is defined as a change in the process design entailing benefits such as reduced energy demand, costs, materials and emissions, better controllability and safer processes. The emerging technologies are analyzed according to this concept to identify the benefits of the technologies in general. The benefits could likewise be advantageous for solar integration in industrial processes.

2.2. Emerging technologies

There is no clear consensus on the characterizations of an emergent technology. Literature suggests it be defined according to the potential impact that emerging technologies could have on an economy and society (Porter et al., 2002). Furthermore, emerging technologies might be of uncertainty and have properties like novelty and growth (Boon & Moors, 2008; Small et al., 2014). Rotolo et al. (2015) take 5 key concepts into consideration in their definition:

- Radical novelty
- Relatively fast growth
- Coherence
- Prominent impact
- Uncertainty and ambiguity

Based on these theories, emergent technologies in this paper are defined as technologies that are not yet established on a market, fast growing and have a vast potential of impact on economy and society, however, entailing uncertainty as the impact lies in the future.

More precisely this paper distinguishes between two types of emerging technologies:

a. Emerging technologies relating to solar energy supply
b. Emerging technologies linked to process technologies

The first one comprises technologies that focus on expanding the potential through new technologies in the field of solar energy supply, allowing the use of higher temperatures. Examples, therefore, are solar furnaces or solar particle technology. This type of emerging technologies is not necessarily industry dependent but solely expands the potential as it supports a broader temperature range. The second one takes developing process technologies into consideration. These technologies may be process specific but could also be applied to several processes. These technologies allow processes to be executed at a lower temperature, which is beneficial for the integration of solar heat in regions with a low average solar irradiation for non-concentrating collectors. Technologies could also operate in a continuous manner eliminating peak demand. Emerging process technologies often come with distinct features, making them superior to the conventional technology. These characteristics address the aforementioned principle of process intensification. Hence, emerging technologies can be seen as the toolbox for process intensification, where identified concepts of PI are realized.

To set a timeframe, characterizing the development of emerging technologies, the concept of Technology Readiness Levels (TRL) is used. Within this framework 9 different stages of development are defined:

- TRL 1 basic principles observed
- TRL 2 technology concept formulated
- TRL 3 experimental proof of concept
- TRL 4 technology validated in the lab
- TRL 5 technology validated in a relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6 technology demonstrated in a relevant environment (industrially relevant environment TRL in the case of key enabling technologies)
- TRL 7 system prototype demonstration in an operational environment
- TRL 8 system complete and qualified
- TRL 9 actual system proven in an operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

(European Commission, 2015)

2.3. Industrial process heat

Process heating is a crucial part of the manufacturing process of most industrial products. It refers to the required heat in the manufacturing operations of an industrial plant (U.S. Department of Energy, n.d.). It comes with a broad range of diversity regarding temperature, sectors, and countries (Werner, 2006). Process heating can either be fuel, electric or steam-based or a combination of these. Irrespective of the method, heat generation requires a high amount of energy (ESTIF, 2006). Appendix A provides an overview of certain unit operations and the industries where they are employed. This underlines the diverse application areas and the associated impact of changes in these processes. Similar in all processes is the generation and transfer of heat. It is distinguished between direct heating methods, where heat is generated within the material (microwave, induction and controlled exothermic reaction) and indirect heating, which is based on the transport of heat from a source to the material through conduction, convection or radiation (Lawrence Berkeley National Laboratory and Resource Dynamics Group, 2007). Another distinction can be made according to the heat profile of the process. Several authors propose a distinction in the following way:

- Low temperature <100°C,
- medium temperature level between 100°C and 400°C and
- high-temperature level over 400°C respectively.

Low temperature is mostly required for washing, rinsing and food preparation processes. It might also be used for space heating and hot water preparation. Medium temperature processes correspond mostly to evaporation and drying. High-temperature heat levels are required in the manufacturing process for metals, ceramics, and glass (Pardo et al., 2012; Werner, 2006). This distinction of the temperature levels is used throughout the paper.

2.4. Potential

The term potential can be defined in numerous ways taking different limitations of the potential into account. First of all, the technical potential considers the potential when land-constraints and system performance are included. The economic potential further considers costs and thus looks at the economic competitiveness. Moreover, the market potential takes policies, regulations, and incentive into account (Andrews & Jelley, 2013; A. Brown et al., 2015; Lopez et al., 2012). Figure 2 provides a visualization of the limitations of the technical, economic, and market potential.

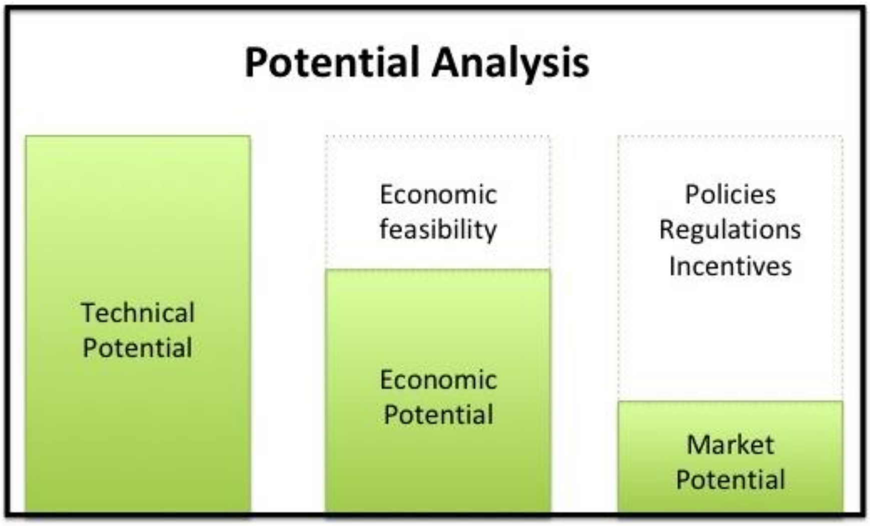


Figure 2 Potential analysis (based on Lopez et al., 2012)

For the purpose of this paper, the term potential is used in two ways. One the one hand, it is used to select emerging technologies; therefore, the potential refers to the possibility of the technology to overcome a certain technical limitation for solar integration in industrial processes. On the other hand, for further analysis, factors such as costs and developmental status of the technology are considered to give an indication of the overall potential and challenges of the technology.

2.5. Roadmap

Garcia et al. define technology roadmapping as a needs-driven technology planning process to help identify, select and develop alternatives to satisfy a set of product needs. Hence, a technology roadmap identifies system requirements, performance targets and the technology alternatives to meet those targets. It is further pointed out that in the case of emerging technologies the roadmap might not include a product context of the technology but goes more into detail regarding the estimated development and the commercialization of the emerging technology and competitiveness of the technology. 3 main purposes of technology roadmapping can be identified:

1. A set of needs and the required technologies to fulfill those needs are identified.
2. It provides a framework to forecast technology developments.
3. It facilitates planning and coordinating technology development for industries (Garcia & Bray, 1997).

This roadmap also aims at addressing these three objectives. In a first step, the current situation and prevailing barriers are analyzed to identify characteristics the emerging technologies have to fulfill in order to enhance solar integration in industrial processes. Moreover, the stage of development and current issues of the emerging technologies are analyzed. The aim is to identify actions which have to be taken and therefore support a further development of the technology. It is mentioned that the roadmap should be adapted to the specific case in order to achieve the best results (Phaal et al., 2004). For this reason, the proposed concept of roadmapping is used as a guideline but has been adjusted for this study.

3. Methodology

The main research question and the sub-questions were answered by the means of a qualitative research, more precisely through desk research and interviews. The research was carried out in three steps: In part A, conventional energy conversion technologies were analyzed with regard to the possibility to be run by renewable energy sources. This transition could be performed easier since the technology is already in place than a switch to emerging technologies. Moreover, solar heat in industrial processes (SHIP) was introduced by the analysis of current projects. The results accentuate current barriers hampering the implementation of SHIP. The identified barriers acted as the basis for Part B where emerging technologies were selected, based on their possibility to overcome current limitations. Moreover, respective characteristics of ET's such as applications, the developmental status of emerging technologies, benefits of the technologies for solar integration and current issues were explored. This information was carried over to part C, where the technologies were subject to a potential analysis.

The methodology used in this framework is tailor-made for this specific purpose. However, it is based on various publications regarding technology roadmapping (Phaal, 2004; Phaal et al., 2004; Reiss, n.d.) and on the structure of the European Roadmap for Process Intensification (Creative Energy, 2007). Figure 3 gives an overview of the general methodology used in this research. The methodology is structured according to the sequence of the sub-questions.

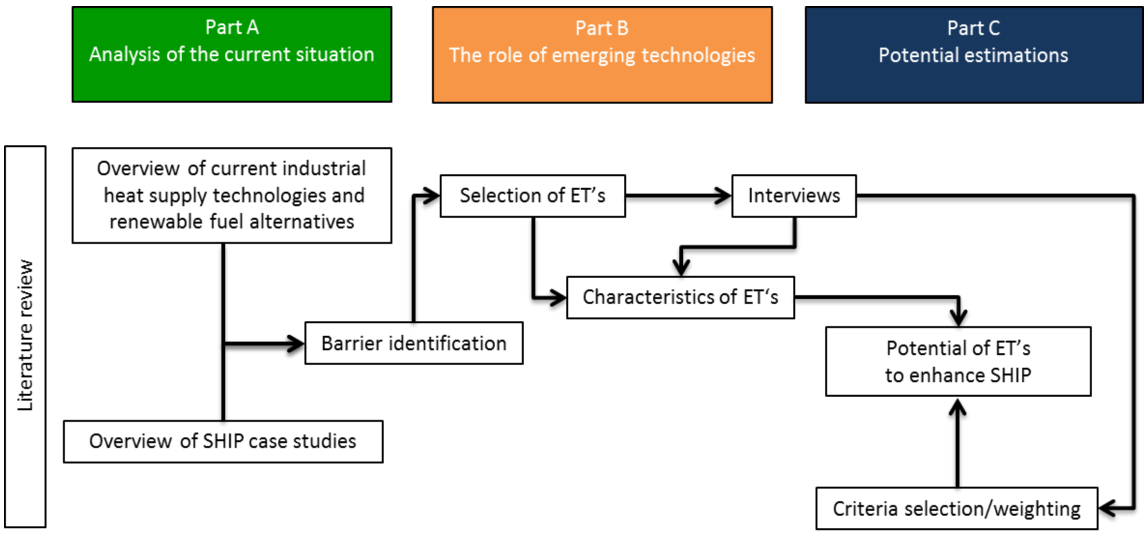


Figure 3 Overview of the general methodology

3.1. Part A - Overview of the current situation and possibilities

3.1.1. Energy conversion technologies

In order to enhance solar integration in industrial processes, it is important to first have a look at conventional energy conversion technologies. These technologies are the core of many industrial processes and are so far mostly driven by fossil fuels. The technologies were explored respectively to the options of renewable energy and more precisely solar integration. The technologies were evaluated according to the temperature profile in comparison to the temperature range of identified industrial processes suitable for solar integration. This analysis pointed out the available options for renewable heat production in current industrial processes as well as current limitations which have to be further addressed.

3.1.2. Overview of current SHIP projects

This section has the purpose of giving an overview of current SHIP installations and the respective characteristics. The analysis is based on the SHIP database (AEE INTEC, 2017). In order to check the completeness and reliability of the database, projects mentioned in literature have been compared to the projects mentioned in the database. This was followed by an analysis of the location, temperature range (°C), industrial sectors of the registered projects and an economic analysis. The economic analysis was based on the indicator €/kWh, with € referring to the total investment costs (excl. VAT) and kWh referring to the annual useful solar heat delivery for 33 projects with available data. Moreover, the conventional fuel price (€/kWh) was considered as a factor. The net present value (NPV) was used as a parameter for the economic calculation under the assumptions given in Table 1:

Table 1 Parameters and assumed values for the NPV calculations

Parameter	Assumed value
Lifetime	20 years
O&M costs	1% of investment costs
Discount rate	8% discount rate

The discount rate was chosen from an industrial perspective, as it is the company that decides to invest in such a project. Steinbach and Staniaszek (2015) estimated in their energy system analysis the discount rate for industrial/commercial companies to be between 6% and 15%, while a report by the IEA, focusing of concentrated solar power estimated the discount rate to be between 5.5% and 12.8% (IRENA, 2012). This justifies the assumption of the discount rate for industries to be 8%. Moreover, a lifetime of 25 years was assumed, as this was stated most often by the respective projects in the SHIP database and 1% of the total installment costs are used as an indicator for O&M costs (EASAC, 2011). The NPV was calculated for the investment costs and for the annual heat delivery and by dividing these two factors the parameter €/kWh was calculated. No loss in yield was assumed over time. Based on the analysis of the location, the temperature range, the industrial sectors and the economic properties of the projects, current barriers to solar integration were identified.

3.2. Part B – The role of emerging technologies

3.2.1. Selection of emerging technologies

The selection of the emerging technologies was twofold. On the one hand, it was based on a previous publication by Muster-Slawitsch et al. (2016), where promising supply technologies for solar integration in industrial processes were identified. On the other hand, the European Roadmap for Process Intensification, introducing 46 emerging process technologies promising for process intensification, provided a basis for the selection of the process technologies. These technologies were evaluated according to three different criteria:

a. Does the technology come with an increase in heat transfer coefficient?
b. Is the process carried out in a different manner leading to lower temperature requirements?
c. Does the technology show smoother process characteristics, such as continuous processing?

These questions were answered in comparison to the conventionally employed technology. The criteria address identified bottlenecks of solar integration and therefore explore the benefits a technology holds to overcome these limitations. One the one hand, a lower temperature demand is desirable, which is especially interesting as a lower process temperature entails a higher efficiency of the solar plant for non-concentrating collectors in regions with low solar irradiation. This can be achieved by a higher heat transfer coefficient enabling a lower gradient between supply and process temperature and therefore reduce the required supply temperature. A lower temperature supply could also be achieved if the process is run in a different manner requiring a lower temperature. On the other hand, smooth/continuous processes facilitate solar integration due to the absence of a peak heat demand, simplifying the design of the system. These criteria were rated with X, stating that the technology comes with the respective feature, XX which means that the feature is more pronounced and XXX, which means that the addressed feature is the key feature of the technology. If a technology was attributed with at least two X, either in two separate categories or twice in one category, the technology was selected as shown in Table 2.

Table 2 Selection of the technologies

Technology	Lower T° demand than conventional technology		Smooth process characteristics	Decision
	Increased heat transfer coefficient	Lower process temperature		
Technology 1	X		X	Yes
Technology 2	XX			Yes
Technology 3	X			No

3.2.2.Characteristics of emerging technologies

Several factors which could facilitate or hamper solar integration in industrial processes have been considered for each technology. In a first step a short overview of the working principle was given, followed by an analysis of the addressed PI strategy and conventional technologies which the emerging one could replace. Secondly, the application areas of emerging technologies were identified for several reasons:

a. The technology might not be developed to the same extent for different application fields.
b. Some application areas might be more suitable for solar integration than others.
c. A broad application area, in many different processes or an application which is very energy-intensive increases the impact emerging technologies could have on solar integration.

The application areas were analyzed according to the development status of the respective technology. The development stage was based on the Technology Readiness Level (TRL). The application areas were split into ones with solar integration and ones without solar integration. Moreover, current issues of the technology were explored in order to determine required actions. Lastly, the integration barriers which these technologies address were identified with regard to enhancing solar integration in industrial processes.

3.3. Part C – Potential estimation

3.3.1. Criteria selection and weighting

This section was based on a previous potential estimation for emerging technologies by Brunner et al. (2011). The criteria were slightly altered in their definition and some were combined or added. Moreover, a distinction between supply and process technologies was made resulting in a final of 7 criteria for process technologies and 6 for supply technologies (Table 3). The rating of the criteria was also extended to a range from 1-5 instead of -1 to 1, to achieve a more accurate weighting. Moreover, a sensitivity analysis was carried out underlining the influence the weighting has on the outcome of the potential analysis. The percentage of the reached points was compared to the overall points (35 for process and 30 for supply technologies) and multiplied by 100 as a factor for comparison. Lastly, studies regarding the quantitative potential were integrated into the technical analysis with the aim to back up results from the qualitative assessment. This was conducted for technologies were qualitative studies were available. As emerging technologies are quite immature, specific quantitative estimations are often not obtainable. For this reason, more general studies were chosen; however, it can be assumed that the found implications also relate to the specific technology.

Table 3 Criteria for the potential estimation

Process Technologies	Supply technologies
Multiplicativity	Multiplicativity
Development status	Development status
Easiness of integrating the emerging technology in industrial processes	Easiness of integrating the emerging technology in industrial processes
Easiness of solar integration in the emerging technology	Efficiency
Efficiency	Costs
Costs	Quality
Quality	

The criteria were defined in the following way:

Multiplicativity

This criterion takes the impact of the emerging technology market into account. Therefore, a technology which is employed in many different applications or in few applications, however with a huge energy demand was ranked highly in this category.

Development status

The development status of the technology is significant in the estimation of the potential, as a technology will only be deployed widely when it has been proven effective in various demonstration plants. Table 4 shows the allocation of points according to the TRL of a technology.

Table 4 Allocation of points relative to the TRL

Ranking	TRL
5 points	9
4 points	7 and 8
3 points	5 and 6
2 points	3 and 4
1 point	1 and 2

Easiness to integrate the emerging technology in industrial processes

This criterion describes the effort which has to be made in order to integrate emerging technologies in the process. If they can easily substitute the conventional technology without entailing further adjustments or even eliminating the need for certain process steps, the technology was ranked in the first category (5 points). The second option refers to technologies where an implementation was feasible; however, the incorporation of the technology involves minor changes in the process operation (3 points). The last one addresses technologies where an implementation was difficult as the process has to be significantly altered, for example, new process steps might be needed before or after the use of the technology (1 point).

Solar integration (SI) within the emerging process technology

This parameter describes the easiness for solar integration in the emerging process technology. If the technology turned out to be extremely promising for solar integration, the technology was ranked in the first category (5 points). If the integration is possible but takes some effort and adjustments it was ranked in the second category (3 points). The third one addresses technologies where a solar implementation was possible but in general not necessary for the process. However, solar integration could enhance the efficiency of the process (1 point). Consequently, this criterion was not applicable to supply technologies.

Quality of product

The quality of the product can either be attributed better, same or worse depending on the specific attributes of the product for emerging process technologies. For supply technologies, this criterion referred to the reached temperature range in comparison with the conventional technology and was therefore attributed higher (5), same (3) or lower (1).

Efficiency

The efficiency of solar supply technologies was based on the conversion of solar irradiation to thermal energy. For process technologies, mainly energy savings were used as an indicator. It was therefore analyzed if the process is carried out at the same quality with a reduced energy demand compared to the conventional technology. The efficiency improvement for process and supply technologies were either attributed low (1), which means that there are no or only really small efficiency gains. Medium (3), implying that there are improvements but they are not the key benefit of the technology, which would then relate to a high ranking (5).

Installment costs

Installment costs compared to the conventional technologies were analyzed, which can be attributed higher, same or lower and are therefore assigned 1, 3 or 5 points.

The rating of criteria was carried out by a literature review as well as by the means of the questionnaire. The criteria multiplicativity and development status were ranked based on the identified applications. Moreover, it cannot be assumed that each criterion influences the overall potential to the same magnitude. For this reason, the questionnaire also included a section about the weighting of criteria.

3.3.2.Questionnaire

The interviews were carried out by e-mail communication with different research facilities working on emerging technologies. The interviewees are partners in the INSHIP project and conduct research on these technologies with regard to solar integration (Table 5). The interviews were conducted for two reasons:

I. To gain insight into current research activities with regard to the following parameters:
   a. the development status of the technology,
   b. benefits for solar integration,
   c. application areas,
   d. and current issues of the technology.

II. To have a more objective way of weighing and ranking the criteria, since they were weighed by several experts.

The questionnaire was structured into 6 segments, where the first four addressed the technology itself and in the last two the experts were asked for their opinion regarding the weighting. On the one hand, they were asked to allocate points to the aforementioned criteria regarding the technology they are working on. In case that there were two responses for one technology, the point average was taken. On the other hand, an inquiry was conducted on the weighting of the criteria. This was done in order to check if a certain criterion has more impact on the overall potential than another one. The acquired information was used in order to answer sub-questions four and five. The complete questionnaire can be found in Appendix B. If information of one of the interviews is used, it is referred to as (p.c. last name, date of reply) throughout the paper.

Table 5 Questionnaire interviewees and respective topics

Name	Institution	Topic	Date of reply
Evan Johnson	METU	Particle technology including heat exchangers	06.04.2018
Vikas Patil	ETHZ	Solar reactors for lime, metallurgy and solar fuels production	04.04.2018
Aris Bonanos	CYI	Multi-effect distillation with film plate heat exchangers	29.04.2018
Gilles Flammant	PROMES CNRS	Solar Furnaces high and high-temperature particle receivers	05.04.2018
Diogo Canavarro	UEVORA	Solar Tower systems for metallurgy, lime, fuel production	05.04.2018
Joachim Koschikowski	Fraunhofer ISE	Membrane distillation	06.04.2018
Guillermo Zaragoza	CIEMAT-PSA	Membrane distillation in desalination	06.04.2018

4. Energy conversion technologies

This chapter deals with current energy conversion technologies regarding heating and cooling options. Firstly, a short overview of the technologies is given, followed by an assessment regarding the temperature level and renewable fuel options. This serves as an indication of the possibility to shift towards renewable alternatives for heat production. Most industrial processes are based on these heat supplying technologies, underlining the potential of renewables, especially solar driven alternatives to replace fossil fuels. As these technologies are already in place, a transition could be performed easier and is therefore explored, before looking into emerging technologies facilitating the implementation of solar driven industrial processes.

4.1. Conventional heat supply technologies

Conventional heat supply technologies can either run on fuels, electricity or steam. Fuel-based options refer to furnaces, ovens, heaters, and kilns, which are all mostly run on fossil fuels. However, renewable sources such as biomass or biogas pose an option. Solar-generated steam can also be employed for example for water preheating in a boiler, in the cold reheat line or directly in high-pressure turbines in a boiler (Suojanen et al., 2017). Moreover, designs for solely solar driven boilers have been explored (Abrams, 2012; Muñoz et al., 2009). Arc furnaces, induction heaters, lasers, microwaves and resistance heating are examples of electrically driven technologies (Lawrence Berkeley National Laboratory and Resource Dynamics Group, 2007). These could naturally be run by electricity from renewable energy sources. However, since this paper focuses on thermal options for industrial processes, these will not be regarded in detail in this chapter, however, are considered in the analysis part. The fuel-based technologies are combined and further referred to as conventional heat supply technologies.

Geothermal energy poses another option for industrial heat generation. Geothermal energy can be extracted from hot groundwater reaching about 100°C. However, this option is really location-dependent (United States Environmental Protection Agency, 2016). Secondly, heat pumps are used to pump or supply heat from or to the ground, which is at a quite constant temperature due to the sun´s irradiation. Heat pumps come with one big advantage: energy saving. That is due to the fact that the energy needed for transferring heat is 3-5 times less than the actual heat transferred (Andrews & Jelley, 2013; Von Cube & Steimle, 1981). Heat pumps generally supply temperature at around 50°C to 70°C (United States Environmental Protection Agency, n.d.). Lastly, deep and enhanced geothermal systems are an option for achieving higher temperatures. However, as costs are quite high, this is only economically feasible in areas with high thermal activity (United States Environmental Protection Agency, 2016). There are also several options for solar integration in heat pumps. Solar heat can, for example, be employed in the storage part of the system or for higher temperatures in the evaporator. The integration of solar heat does not alter the temperature range significantly but mostly leads to a better performance and efficiency of the heat pump (Chua et al., 2010; Lerch et al., 2014).

Another efficient way of generating heat is through CHP plants. Temperatures of up to 480°C can be reached depending on the technology used (U.S Department of Energy, 2017). Currently, natural gas is the predominant fuel; nonetheless, nuclear, biomass and biogas are alternatives (ASHRAE, 2015).

4.2. Solar-driven heat supply technologies

Solar thermal collectors convert electromagnetic solar irradiation directly into heat (Goswami, 2015). There are several types of solar collectors ranging from 100°C for flat plate, to 100°C to 300°C for evacuated tube and up to 1000°C for central receiver collectors (Figure 4) (Tiwari et al., 2016). A flat plate collector absorbs solar radiation with a flat black plate. An evacuated tube collector consists of an array of parallel tubes, with a reflecting surface at the back of the panel. Solar radiation strikes an outer glass tube and is absorbed by the blackened out heat pipe. This heat pipe is surrounded by a vacuum in order to reduce heat loss to the environment. The heat pipe contains a fluid, which evaporates. The vapor is transmitted to a heat exchanger and the cooled liquid is returned to the heat pipe. This type of collector is well suited for lower temperatures and areas with less solar irradiation (Shah, 2018). Research has been dedicated to developing designs for higher temperatures. For medium temperature heat supply advanced versions of the mentioned technologies are employed; however, solar concentrating technologies are predominant for medium and high-temperature heat demand. Four solar concentrating technologies are currently available; parabolic dishes, parabolic trough, linear Fresnel collectors and central receivers. Parabolic trough collectors are composed of curved glass focusing the sunlight on tubes on the receiver (Andrews & Jelley, 2013). Parabolic dishes focus solar radiation on the focal point in front of the dish. Linear Fresnel collectors are positioned vertically and focus the sunlight on a receiver above the collectors. Central receivers collect the reflected irradiation with a receiver placed on top of a solar tower (IRENA & IEA-ETSAP, 2015).

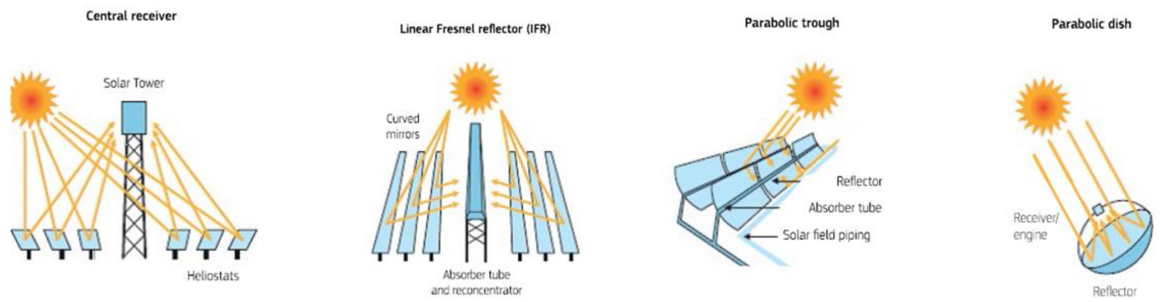


Figure 4 Centralized solar power collector types (European Commission, 2017)

4.3. Analysis of energy conversion technologies

Table 6 summarizes the temperature range with respect to the energy conversion technology. It stands out that for most energy conversion technologies renewable alternatives exist or hybrid installations are possible. However, these alternatives are not yet deployed widely.

Table 6 Heat conversion technologies and their respective temperature range

Technology	Temperature range	Renewable options besides solar	Solar
Ground source heat pump (HP)	<60 °C	Geothermal	Yes
Flat Plate Collector (FPC)	<100°C	-	Yes
Evacuated Tube Collector (ETC)	<300°C	-	Yes
CHP	<480°C	Biomass, biogas, geothermal	Yes
Linear receivers	<550°C	-	Yes
Conventional fuel-based heating devices	>550°C	Biomass, biogas	Various integration points
Central receivers	>550°C	-	Yes

Table 7 presents the temperature range for common industrial processes. Combining the information of Table 6 and Table 7 shows that non-conventional fuel-based technologies mostly operate at a temperature range of below 500°C, whereas many common industrial processes require higher temperatures. For this reason, new technologies should focus on renewable options for high-temperature heat supply. On the other hand, several studies have been conducted exploring suitable industrial sectors with low-temperature demand integration to emphasize the current possibilities, which is promising in regard to renewable energy supply options (Kalogirou, 2003; Krmelj, 2011; Sharma et al., 2017). An overview of these processes is given in Appendix D.

Table 7 Temperature range of common industrial processes (U.S. Department of Energy, 2015)

Unit operation	Applications	Temperature range
Other	Preheating; catalysis; thermal oxidation; incineration; other heating	100°C-5400°C
Fluid Heating	Food preparation; chemical production; reforming; distillation; cracking; hydrotreating	110°C-460°C
Curing and Forming	Coating; polymer production; enameling; molding; extrusion	140°C-650°C
Drying	Water and organic compound removal	160°C-1900°C
Coking	Ironmaking and other metal production	400°C-1100°C
Metal heat treating and reheating	Hardening; annealing; tempering; forging; rolling	500°C-1200°C
Non-metal melting	Plastics manufacturing; food preparation; softening and warming	1000°C-1500°C
Calcining	Lime calcining	600°C-1200°C
Smelting and metal melting	Casting; steelmaking and other metal production; glass production	700°C-1600°C

Figure 5 visualizes the technology options for renewable industrial process heat respective to the reached temperature range and the relating process operations. The temperature range of the renewable options is quite similar to the one defined in Table 6. The figure also emphasizes the fact that several renewable options for process heat in the low and medium temperature (T <200°C) are available. Especially solar process heat seems to be a really promising option as it covers low, medium and high-temperature processes. In the low-temperature range, other renewable options could compete with solar heat. In the high-temperature range only biomass and electric heating, based on renewable resources pose options. Moreover, hydrogen could be produced via electrolysis, which could be run by renewable resources and then further be used as a fuel (Office of Energy Efficiency & Renewable Energy, n.d.). There is also the possibility for hybrid systems, a combination of energy sources and heating methods, which allows to optimize the energy utilization and lead to a higher thermal efficiency (Lawrence Berkeley National Laboratory and Resource Dynamics Group, 2007).

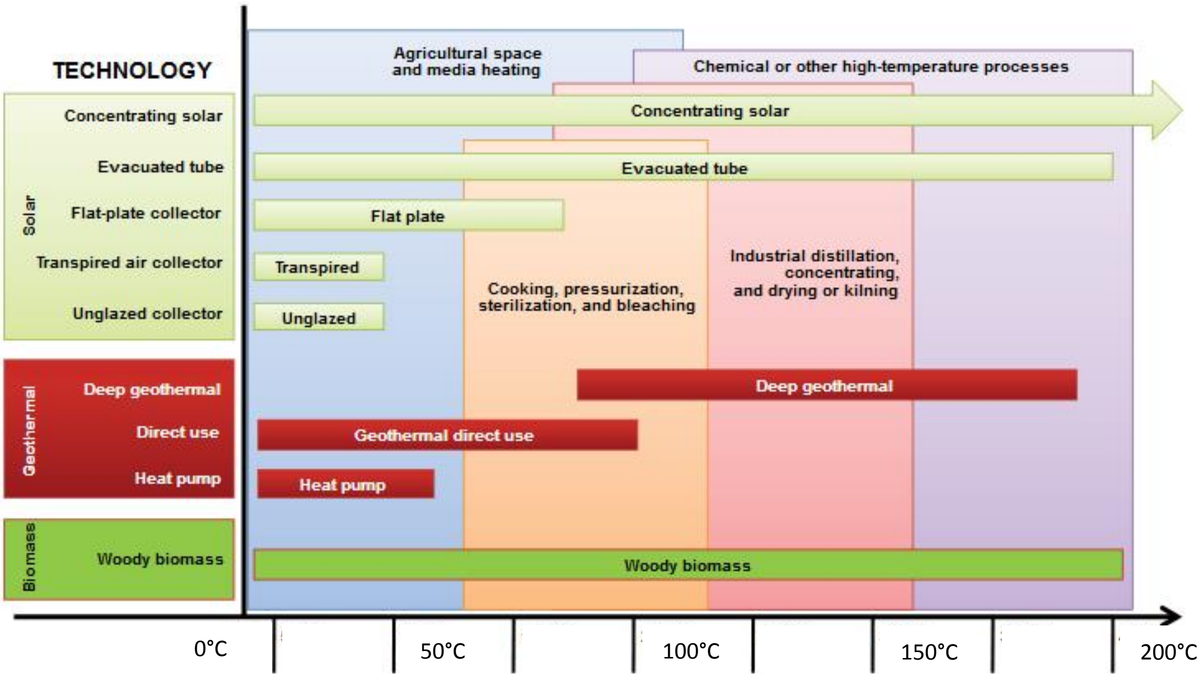


Figure 5 Renewable options for industrial process heat (United States Environmental Protection Agency, n.d.)

This study answers subquestion 2 as possibilities to substitute fossil fuels with renewable energy sources for energy conversion technologies are explored. While in the low-temperature range several renewable alternatives exits, the results also emphasize the need for renewable high-temperature heat supply technologies.

5. Overview of the current status quo of solar heat integration in industrial processes

The solar heat in industrial processes (SHIP) plants database is built on the initiatives of companies to state their efforts in implementing solar heat in industrial processes. Currently, 305 projects are registered, which serve as a good basis for an overview and comparison of projects regarding location, sector and temperature range. Several mentioned projects in publications were checked for their availability in the SHIP database in order to give an indication of the overall completeness and reliability (Table 8). The database can be regarded as quite exhaustive since the key projects found in literature are included. Only a few projects are mentioned which are not stated in the database. However, these do not necessarily refer to smaller sized (kW_{th}) projects, but in the case of LACO and brick drying in Laterizzi are quite big. Overall the database is expected to give a representative overview of the typical project and is therefore utilized for further analysis. Not all data is available for every project in the database, for this reason, the succeeding analysis focuses on the projects with comprehensive available data.

Table 8 Analysis of the reliability of the SHIP database

SHIP Project	Size of project (kW_{th})	Present in SHIP database	Mentioned in:
Tyras, Greece	728	Yes	(UNEP, 2010)
Hellenic Copper mines, Chile	27510	Yes	
Gösser Brewery, Austria	1064	Yes	(de Lange, 2013)
Parking Service Castellbisbal, Spain	357	Yes	(UNEP, 2010)
Keminova Italiana s.r.l., Italy	63	No	
El NASR Pharmaceutical	1330	Yes	
Montesano, Spain	203	Yes	(Heß & Oliva, 2010)
Laguna, Germany	39.9	Yes	
Steinbach und Vollmann, Germany	280	Yes	
Lammsbräu, Germany	50.75	Yes	
Meat Factory Berger, Austria	746,9	Yes	(Henneke, 2012)
Brick drying at Laterizzi, Italy	1200	No	
Lácteas Cobreros (LACO), Spain	1000	No	
Emmi Dairy, Switzerland	360	Yes	
LESA, Switzerland	67	Yes	
Dürr Paint Oven, Germany	74	No	
Frito Lay, USA	354.6	Yes	

Figure 6 shows the development of the number of projects that went into operation with respect to the time period. The number of new projects has been increasing, reaching 111 new projects from 2011 to 2015. This underlines the efforts made in order to enhance solar integration in industrial processes. Since the timespan in the last column only includes two years in comparison two 5 years in the other scenarios, fewer projects were registered.

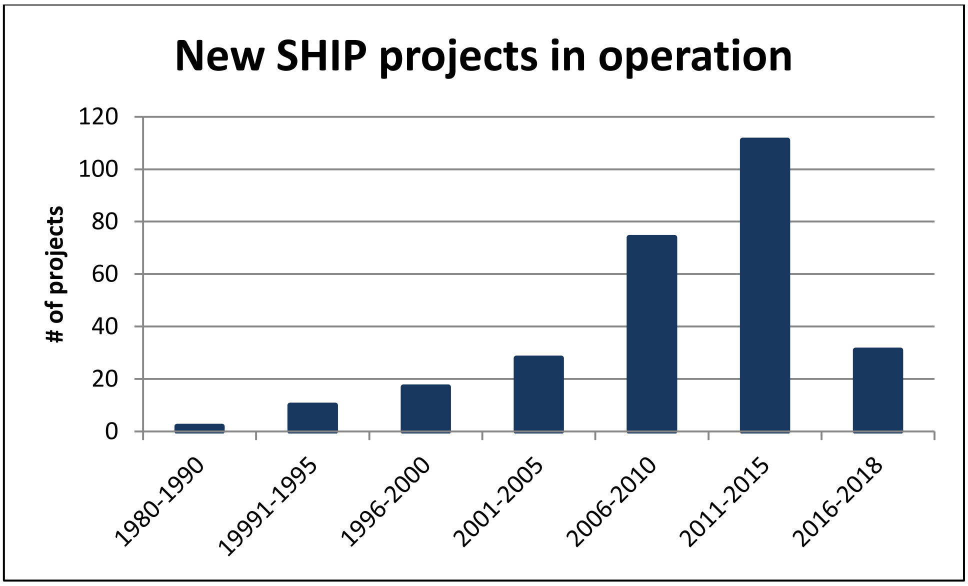


Figure 6 New projects in operation

5.1. Location analysis

This analysis focuses on identifying certain patterns concerning the location of SHIP projects. The locations of the SHIP projects are visualized in Figure 7.

Figure 7 Location of SHIP projects (AEE-INTEC, 2018)

The outcome of this analysis identifies Mexico and India as the locations of 40% of all projects. In Europe, most projects are installed in Austria and Germany and the northern-most project is located in Sweden. In Southern Europe, Greece and Spain are the primary locations while in the Middle East Jordan and Israel predominate. Another hotspot can be identified in the US, where most projects are located on the West Coast. In Africa, only South Africa shows significant numbers with ten installations. Besides India, China shows promising numbers in Asia (Table 9). Surprisingly, no projects have been registered for Australia.

Table 9 Number of registered projects per country

Country	# of projects
Mexico	65
India	54
Austria	29
Germany	25
United States	18
Spain	15
Greece	13
China	13
South Africa	10
Israel	6
Jordan	4
Oman	2
Tunisia	2
United Arab Emirates	2
Saudi Arabia	1

Based on this several implications can be drawn:

- Solar radiation can be regarded as an enhancing factor, as most projects have been implemented in areas with high solar irradiation.
- A low development status of a country can be regarded as a limiting factor, even if solar irradiation is highly available, as in the case of many African countries.
- Countries that have a high solar irradiation and are in transition towards becoming industrialized are promising areas for SHIP.
- Countries that are well-developed have the ability to implement SHIP projects even if there is less solar radiation.

5.2. Temperature range

Regarding the process temperature range, most of the projects are found in the low-temperature range with temperatures below 120°C. The required temperature refers mostly to the unit operation and is to a lesser extent related to a specific sector. Only 19 projects out of 305 exceed 120°C in their process temperature, reaching up to 200°C. All except two of these projects have been installed after 2010. This could be a hint for current research developments in the medium temperature range. There is no indication that the location of the project influences the required process temperature or sector. The results of this analysis are quite consistent with the outcome of a research conducted by Farjana et al. (2017), where all but two sectors use solar heat mostly in processes below 120°C. Only the sectors Bricks and Blocks, Plastics, and Metals have integrated solar heat predominantly in processes above 120°C. This underlines the current feasibility of solar integration in low-temperature processes, emphasizing the need to reduce current process temperatures in order to enable solar integration. Moreover, a higher market penetration of solar technologies for medium and high-temperature processes is desirable.

5.3. Economic analysis

The economic analysis is based on the net present value of the indicator €/kWh, where € refers to the total investment costs, (excl. VAT) and kWh refers to the annual useful solar heat delivery. As data regarding those two factors is limited, this analysis is based on 33 projects with available data. Therefore, the limited reliability of this assessment has to be noted. Moreover, a lifetime of 25 years was assumed and a discount rate of 8%. The results show an average of 0.06€/kWh. The highest cost of solar heat production reaches 0.22€/kWh in manufacturing, requiring high temperatures of 165°C-180°C (Table 12). Table 10 and Table 11 show the average cost of heat supply in relation to the useful heat delivery in MWh/a and to the installed thermal power (kW_{th}). Both parameters indicate that the project size influences the cost of heat supply significantly. Smaller projects come with higher costs, while for bigger projects costs are lowered.

Table 10 Average cost of heat supply in €/kWh based on the useful heat delivery (MWh/a)

	<100 MWh/a	100-500 MWh/a	500-1000 MWh/a	>1000 MWh/a
Average cost of heat supply €/kWh	0.09	0.05	0.03	0.03

Table 11 Average cost of heat supply in €/kWH based on the installed thermal power (kW_{th})

	<100 kWth	100-500 kWth	500-1000kWth	>1000 kWth
Average cost of heat supply in €/kWh	0.08	0.05	0.02	0.04

In comparison to the conventional fuel price paid by the respective company, the solar option is in every case the cheaper one except for two, of which one is based on a rather unrealistic fuel price (Table 12). These calculations are in line with estimated solar heat generation costs of 0.02 €/kWh to 0.08 €/kWh by Heß and Oliva and 0.04 €/kWH to 0.12 €/kWh from ESTIF. It is stated that the costs are dependent on location, process and temperature range (ESTIF, 2015; Heß & Oliva, 2010). The results underline the cost-competitiveness of solar process heat.

Table 12 Economic analysis

Name of Company	Installment costs excl. VAT in €	Specific useful annually heat delivery in MWh/a	€/kWh	Fuel price €/kWh
Ruyi textile	1 699 962	5952.99	0.03	0.04
Shandong Linuo	1 000 000	4313	0.02	n/a
Hellenic Copper mines	400 000	1130	0.03	n/a
Brauerei Hald	16 780	9	0.18	n/a
Hustert	127 400	95	0.13	n/a
Hütt Brewery	96 000	400	0.02	n/a
Penzkofer Autolackiererei Germany	6 000	11	0.05	0.09
Tyras S.A.	173 000	620	0.03	0.12
B.G Chitale	63 049	387.8	0.02	n/a

Chelsea Jeans	54 640	876	0.01	0.04
Harita	191 200	648	0.03	n/a
India Tobacco Division	114 061	450	0.02	n/a
OCV glass fibre	7 080	33	0.02	n/a
Sharman Shawls	40 000	250	0.02	0.08
Golan Winery	200 000	212	0.09	n/a
Izra`el's Kitchen	44 600	140	0.03	0.08
Kibbutz	20 000	45.2	0.04	n/a
Nuova Sarda Industria	140 000	500	0.03	0.07
Matatlan Dairy	23 039	67.3	0.03	0.08
Silampos, S.A	100 000	139	0.07	0.0001*
Hofigal S.A.	28 000	35	0.08	n/a
Arma Plant	360 00	50	0.07	n/a
Fasa Valladolid	100 000	128	0.07	n/a
Harlequin	32 942	42	0.08	n/a
Montesano Jere de los Caballero	131 250	172	0.07	n/a
Nissan Avila	140 000	480	0.03	0.03
Emmi Dairy	300 000	255	0.11	0.09
Inter Rubber	3 600	50	0.01	n/a
Masdar City solar	92 000	40	0.22	n/a
Battenkill	45 223	39.9	0.11	n/a
Browns brewing Co	46 838	41	0.11	n/a
Stapleton	650 000	831	0.08	n/a
Grammer Solar Vietnam	140 000	300	0.04	n/a

*not included as this is an unrealistic number

5.4. Sector analysis

Within this analysis well-suited sectors for SHIP integration are identified. More than ¾ of all registered projects are in manufacturing with food products being the dominant subsector with 109 SHIP projects. Within this subsector, solar process heat is mostly integrated into cleaning, cooking, and boiler preheating processes. Other sectors mentioned are agriculture, mining and quarrying, electricity gas steam and air conditioning supply, construction, water supply, sewage and waste management and remediation activities, transporting and storage, accommodation and food service activities, information and communication, professional, scientific and technical activities, human health and social activities and other service activities (Figure 8). That goes to show the wide variety of potential sectors for solar heat integration. Within these sectors, the main application of solar heat is in the categories cleaning, drying, other process heat and general process heat processes. It cannot be said that certain applications of solar integrated heat are found in a certain sector, but that the application is case specific. The same observation was made by Farjana et al. (2017) stating that industrial processes cannot be generalized or categorized because of diverse conditions. Yet the analysis gives reason to consider the food processing sector as an already well-developed sector where many integration options have been explored. However, it also shows that pilot projects have been introduced in many different sectors, underlining the effort taken so far.

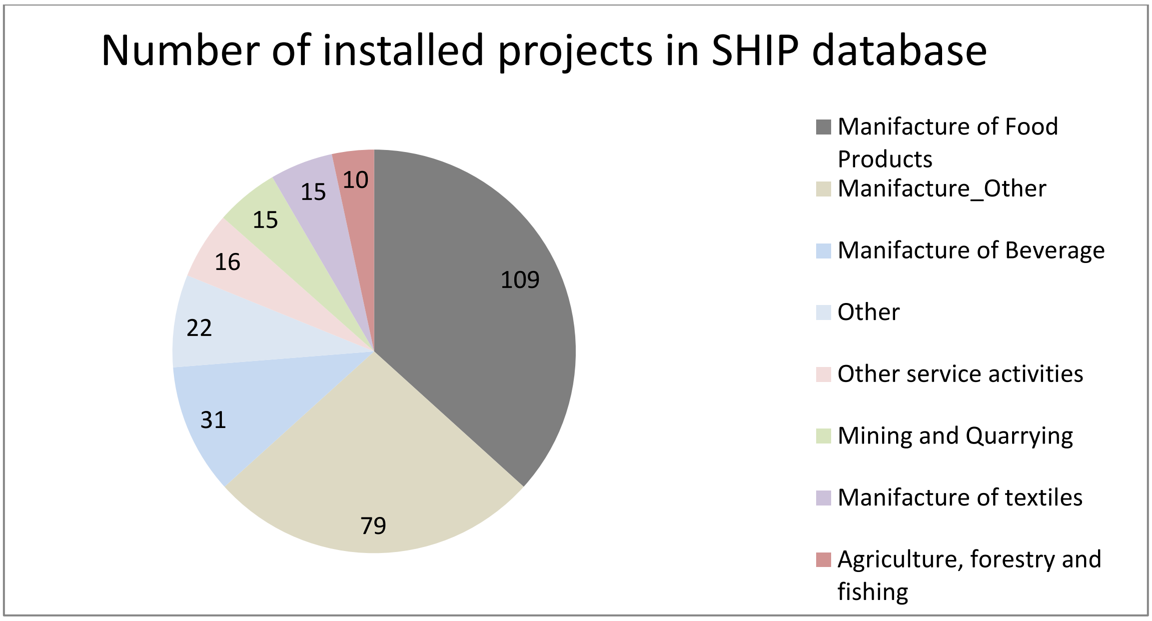


Figure 8 Number of installed projects per sector(based on AEE INTEC, 2017)

5.5. Implications of the analysis

From this overview several conclusions for this paper are drawn:

1. The number of projects has been increasing, emphasizing the effectiveness of research efforts.
2. Solar radiation and the development status of a country are significant factors in determining the implementation potential of a country and should, therefore, be considered as potential barriers.
3. The prevalent temperature range is from 20°C to 100°C, underlining the importance of reducing temperature demand of current processes and the need for solar technology development for medium and high-temperature processes.
4. Economic feasibility is given in the long-term and is, therefore, to be advocated in industrial planning processes.
5. Bigger projects come with reduced costs, while for smaller installations costs are higher.
6. The application of solar heat is not particularly related to the sector but to the unit operation.
7. Food processing can be regarded as a well-suited sector for solar integration and has already been extensively explored. Nonetheless, almost all sectors have shown efforts in implementing solar heat in industrial processes. This stresses the potential solar heat integration already has in industrial processes.

5.6. Barrier identification

Based on the analysis of the SHIP database, three main barriers can be identified:

- Solar irradiation
- Temperature level
- Costs

In addition, a literature study concerning the barriers of solar heat integration identified the following impediments: lack of awareness of new technologies, confidence only in long-term proven technology, no policy support and lack of suitable planning guidelines as well as lack of education and training (ESTIF, 2006; Sharma et al., 2017). While these general issues need to be mostly addressed by policymakers and industries, the lack of technologies for a specific purpose, the difficulty of integration into existing systems, the lack of storages and the diversity of industry, requiring tailor-made solutions relate more to the technical side and could, therefore, be potentially overcome by technological improvements. Four main technical bottlenecks, which hamper solar integration in industrial processes, can be identified:

- High process temperature
- Low thermal transfer coefficient requiring large temperature gradients
- Fast heating rates
- Varying process loads, referring to batch processes with a high peak demand (Muster & Brunner, 2015).

The selection of technologies was based on the possibilities of the emerging technologies to overcome these bottlenecks and therefore pose promising options for solar integration. Throughout the paper, the term "bottlenecks" is associated with those four limitations. While the term barrier refers to general issues of solar integration, including technical challenges, which could naturally relate to the identified bottlenecks.

6. Role of emerging technologies

6.1. Link between solar process heat and emerging technologies

There are various ways to integrate solar heat in industrial processes. Similar to the distinction of the emerging technologies into supply and process ones, solar heat integration can also be distinguished into the integration on a supply level and the integration on a process level. On a supply level, solar heat can be integrated into the heating of make-up water, heating of supply heat storage and heating of the heat supply network. On a process level, solar heat is incorporated in the actual heating of processes/vessels, the heating of the process medium and the heating of the process heat storage (Figure 9) (Muster-Slawitsch et al., 2015). In general, it can be said that the preheating of the feed is often possible, while the integration within in the process technology could pose several problems.

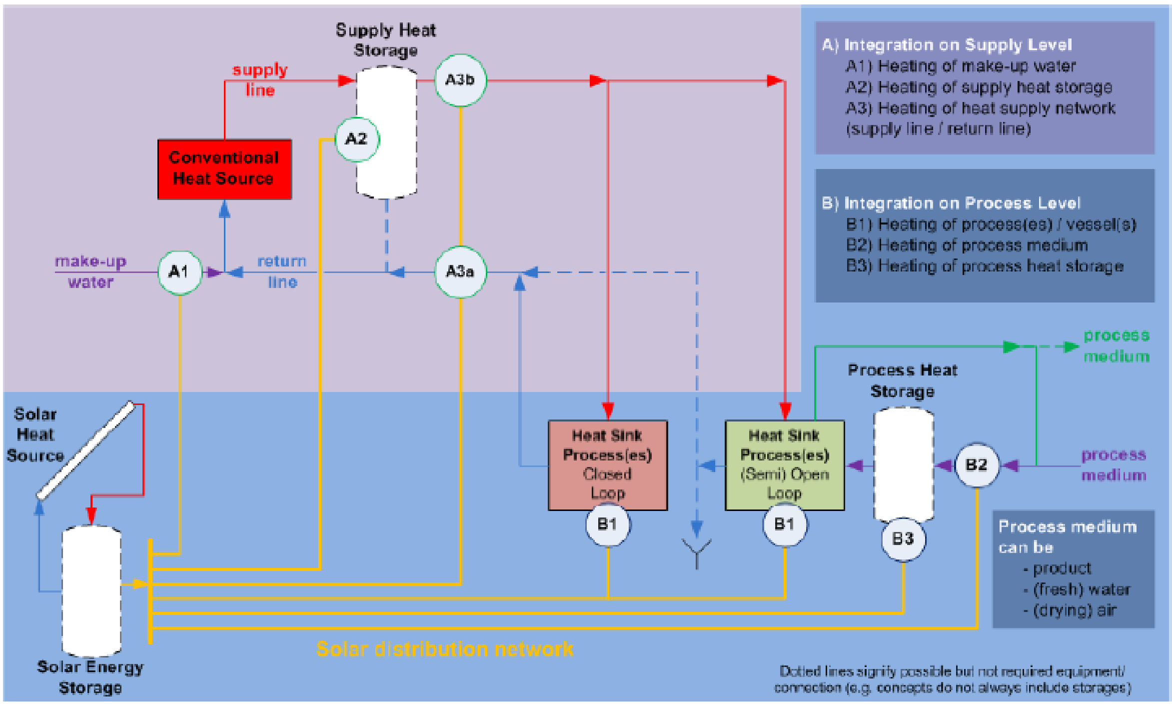


Figure 9 Possible integration points for solar process heat (Muster-Slawitsch et al., 2015)

Emerging technologies come with certain properties, which make them superior to the conventional technology. These characteristics impact the potential of solar heat integration. For this reason, general properties of emerging technologies are analyzed in regard to their influence on solar integration.

First of all, a higher efficiency is one of the main goals of process intensification and is therefore often addressed by emerging technologies. These efficiency gains can stem from an increased mass and heat transfer, which could allow reactions to be carried out at shorter residence times. While this, on the one hand, is obviously desirable, on the other hand, poses a limitation for solar integration, since it could entail a low-temperature gradient between supply and return line, requiring a large mass flow in the collectors. This leads to the need for large pumps, which increases costs. One example of a technology dealing with this issue is spinning disc reactors. Spinning disc reactors come with a really high heat transfer coefficient, which is promising for solar integration, however, the small temperature difference between supply and return line due to a short residence time makes it unsuitable for solar integration. The mass flow could be reduced by designing the heat exchangers for a larger temperature driving force, however, this would require higher temperatures, which decreases the efficiency of the solar collector for non-concentrating collectors in areas with low irradiation (Muster & Brunner, 2015).

In contrast, an increase in efficiency could also be beneficial for solar integration. A higher efficiency is likely to reduce the costs of the process, which could increase the cost-effectiveness of the system with solar integration. This alone is not a convincing argument, as it would even bring more cost benefits without solar integration. However, as in the case of combined systems, such as solar reactors, it is considered a reasonable benefit. A catalytic foam reactor, for example, is 10 times more efficient than a packed bed reactor (Netherlands Organization for Scientific Research, 2008). Hence, cost-savings could be achieved, which could make the integration of solar process heat cost-effective in the case of catalytic foam reactors, while it might still be a barrier for packed bed reactors.

It is also known, as defined by the Arrhenius equation ($k = A * e^{-\frac{Ea}{R*T}}$), with A being the pre-exponential factor, T the absolute temperature, E_a the activation energy for the reaction and R the universal gas constant, that an increase in temperature accelerates the reactions rate. This would mean that in case the reaction rate is increased by the characteristics of the emerging technology, the temperature could be reduced, which would be advantageous for solar integration. Therefore, an increase for example in mass transfer could allow for processes to be carried out at a lower temperature. One example for this concept are impinging streams reactors, which come with a major increase in mass transfer compared to other technologies (Creative Energy, 2007), which increases the reaction rate and could therefore allow a reduction in temperature.

Based on Fournier's law the heat flow is defined by the following equation: $Q = h * A * \Delta T$, with h being the heat transfer coefficient, A the surface area and ΔT the temperature difference between the surface and the fluid. Therefore, an increase in the heat exchange surface area or in the heat transfer coefficient lead to an increase in the heat flow. This in turn allows for the temperature gradient to be reduced. This means that an emerging technology, which either increases the heat transfer area or the heat transfer coefficient could enable a reduced temperature demand and can therefore be regarded as beneficial for solar integration.

6.2. Selection of the technology

Besides these general characteristics, several technologies have been proven especially promising for solar integration due to their potential to overcome the identified bottlenecks based on the introduced framework (Table 13). As aforementioned the identified bottlenecks are

a) high process temperatures
b) low thermal transfer coefficients
c) fast heating rates
d) varying process loads, leading to a high peak demand (Muster & Brunner, 2015).

Based on these bottlenecks, 3 different criteria for the selection of process technologies were chosen, as they are expected to be promising for overcoming the previously mentioned limitations. High process temperatures can be addressed by an increase in heat transfer coefficient as well as in a change of the process towards a process requiring a lower temperature. Obviously, a high heat transfer coefficient addresses bottleneck b. Smooth process characteristics, e.g. a switch from batch to continuous production, eliminates a high peak demand and is therefore chosen as a criterion. A detailed assessment and reasoning behind the selection of the technologies can be found in Appendix C. The selection of the supply technologies was based on a previously published paper, where the selected technologies were identified promising for solar integration since they allow for a higher temperature heat supply (Muster-Slawitsch et al., 2016). Namely, these are solar furnaces and solar particle technology. This distinction comes from the fact that on the one hand, lower temperatures are promising for solar process heat in areas with a low solar irradiation as it simplifies the supply side design of the system and increases the efficiency of the collectors. On the other hand, several processes will always require high-temperature heat supply. For that reason, research on high-temperature supply technologies is necessary.

Table 13 Selected emerging process technologies and emerging solar supply technologies

Technology	Lower T° than conventional		Smooth process characteristics
	High heat transfer coefficient	Change in process->lower T°	
Extended heat exchange surfaces	XX		
Pervaporation		XX	
Membrane distillation		XX	
Oscillatory baffled reactor	XX		XX
Microchannel reactor	XXX		X
Pulse combustion drying	XX		
Solar furnaces	Based on Muster-Slawitsch et al., (2016)		
Solar particle technology			

6.3. General information and applications

The selected technologies are introduced according to the following structure: First of all, a short explanation of the working principle is given, followed by an introduction on why this technology has the potential to replace the current technology and how the characteristics enable process intensification. Lastly, applications and the development status of the respective technology are explored.

6.3.1. Extended heat exchange surfaces

Working principle, advantages over conventional technologies and underlying PI principle

Extended heat exchange surfaces refer to technologies where an additional surface area is added with the aim to increase the heat transfer rate in the allowed pressure drop (Bergman et al., 2011). One the one hand, fins are employed to increase the internal heat transfer area (Bergman et al., 2011; Kraus et al., 2002). On the other hand, an additional heat exchange surface next to the existing one can be employed. In this case, however, more equipment is needed, which is contradicting to the PI goal of minimizing plant size (Muster-Slawitsch, 2014).

Applications

Extended heat exchange surfaces are already employed in many commercial applications mostly without solar integration. There are, however, several examples where extended heat exchange surfaces are integrated with solar heat. Based on the information obtained from Table 14 it is argued that extended heat exchange surfaces are used in many technologies in industrial processes. Thus, the impact of this technology to enhance solar integration in industrial processes is estimated to be quite high and is therefore assigned with 3 points as the multiplicativity might be limited by the numerous small size functions, where solar integration requires a lot of effort.

Table 14 Application areas and development status for extended heat exchange surfaces

Solar integration	Application	Development status	Unit operations
Applications without solar integration	- Heat exchangers[1] - Heat sinks in elec. equipment[1] - Conventional furnaces and gas turbines[1] - Boilers[1]	TRL 9	- Process heating - Cooling processes - Space heating/cooling
Applications with solar integration	- Latent heat thermal energy storage (LHTES)[2]	TRL 9	- Process heating - Drying [3]
	- Solar air heaters [4]	TRL 9	- Process heating - Drying [3]
	- Stirred tank[5]	TRL 5	- Mashing
	- Solar stills[6]	TRL 4	- Evaporation and distillation

[1](Gavhane, 2008; Kraus et al., 2002; Nabadi, 2008), [2](Bazri et al., 2018; Pointner et al., 2015; Sciacovelli et al., 2015), [3](Bazri et al., 2018; Kazemi et al., 2018; M. Kumar et al., 2016; Pointner et al., 2015; Sciacovelli et al., 2015), [4](Hosseini et al., 2018; R. Kumar & Rosen, 2011; Naphon, 2005; Tiwade & Pathare, 2009), [5](Muster-Slawitsch et al., 2016), [6](Alaian et al., 2016; Omara et al., 2011; Velmurugan et al., 2008)

6.3.2.Pervaporation

Working principle, advantages over conventional technologies and underlying PI principle

Pervaporation is based on three steps: Solution, diffusion, and evaporation (Uragami, 2017). The feed solution is first heated adjacent to the feed side of the selective dense membrane. Easily permeating components are transferred through the membrane and are withdrawn as vapor on the permeate side due to a lower prevailing pressure. This pressure difference can be induced either by a vacuum or inert gas on the permeate side or through a temperature difference between the two sides of the membrane (Figure 10) (Crespo & Brazinha, 2015).

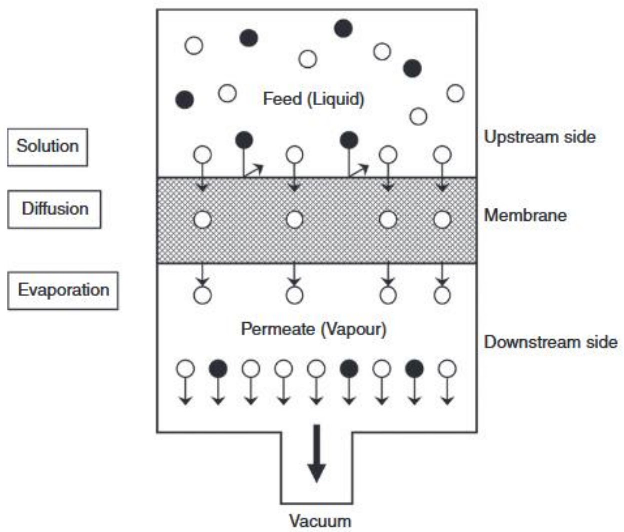


Figure 10 Working principle of vacuum pervaporation (Uragami, 2017)

In pervaporation the membrane acts as the selective barrier. Three different membrane types are used:

- Hydrophilic membranes (polymer/inorganic material) – water is the desired compound
- Hydrophobic membranes (polymer/inorganic material) – organic material is the desired compound
- Organic-organic membranes –reuse and recovery of organic compounds (Q. Wang et al., 2016).

Membrane processes favor a higher selectivity and efficiency by allowing only specific components to permeate the membrane (Muster-Slawitsch et al., 2016). There are several benefits of pervaporation over other separation processes; Compared to membrane distillation (MD) pervaporation requires less energy as only a minor part of components is evaporated and is therefore cheaper. Moreover, PV can achieve good rejection rates for a wider variety of concentrates than reverse osmosis (RO) without increasing costs (Q. Wang et al., 2016). Further on, pervaporation comes with a high selectivity and low environmental impact. It is a very mild process and thus effective for mixtures which cannot survive the harsh conditions of distillation (Muster-Slawitsch et al., 2016). Since dense membranes are used, the risk of wetting and pore plugging is diminished; therefore no pretreatment is necessary, which again reduces costs (Zwijnenberg et al., 2005).

Applications

In principle, pervaporation has already been employed in several commercial applications, however, research is still ongoing for further operations and the integration with solar heat (Table 15). As the flux is a limiting factor, pervaporation is mostly suitable for solutions where a small amount of a substance is to be extracted. For that reason, multiplicativity is assigned two points.

Table 15 Application areas and development status of pervaporation

Solar integration	Application	Development status	Unit operations
Applications without solar integration	- Dehydration of organic solvents[2] - Removal of dilute organic substances from liquids [2]	TRL 9	- Purification - Concentration - Separation
	- Separation of organic-organic mixtures[2]	TRL 7 [1]	- Separation
	- Processing of acids[4]	TRL 4	- Separation
Applications with solar integration	- Desalination[3]	TRL 4	- Purification

[1](de Haan, 2015)’ [2](Smitha et al., 2004)’ [3](Q. Wang et al., 2016; Zwijnenberg et al., 2005), [4](Crespo & Brazinha, 2015; Jullok et al., 2011)

6.3.3. Membrane distillation

Working principle, advantages over conventional technologies and underlying PI concept

Membrane distillation is a thermally driven separation process, where the feed side is in direct contact with the membrane but cannot permeate due to the hydrophobic property of the membrane. Heating the solution allows volatile molecules to transfer the membrane after which the vapor is condensed resulting in high-quality distillate and a concentrated feed solution, where non-volatile components remain (El-Bourawi et al., 2006; González et al., 2017). Similar to pervaporation, membrane distillation also increases the selectivity and efficiency of separation processes (Drioli et al., 2011). There are several advantages over other separation techniques. Firstly, there is no need for high pressure as in RO, which reduces the chances of problems with leaks and pump failure. Secondly, the process is based on simpler design and operation than RO. It is moreover estimated that MD could be cost-effective compared to conventional distillation systems (Blanco Gálvez et al., 2009). In summary, MD is characterized by a theoretical 100% rejection rate, mild operating conditions, relatively low temperature and lower operating pressure (P. Wang & Chung, 2015).

Applications

MD has been researched in regard to various application areas, with desalination being the most prominent one (El-Bourawi et al., 2006) (Table 16). However, Koschikowski states that MD for desalination will only be cost-competitive if several criteria are fulfilled. Most importantly, waste heat must be available for no costs. Therefore, MD will find other application areas where current technologies, e.g RO, are not applicable or cost-competitive. Suitable areas could be processes with high salt concentrations, applications with aggressive or corrosive media or applications where better process control is needed, which is possible due to the properties of membrane distillation. More specifically, extracting of specific valuable substances from diluted waste solutions for recycling, concentrating valuable waste solutions for direct recycling and concentrating of hazardous waste solutions to minimize costs and effort for direct disposal are mentioned (p.c. Koschikowski, J., 10.04.2018). Regarding unit operations, MD is used in separation, purification and concentration processes. Based on this MD is assigned two points for the factor multiplicativity.

Table 16 Application areas and development status of membrane distillation

Solar integration	Application	Development status	Unit operations
Applications without solar integration	– Removal of small molecule containments, such as boron, arsenic, chromium or organic contaminants, as MD comes with very good rejection rates [1] – Recovery of valuable containments as mineral/volatile acids, fruit juices, sugar, alcoholics and volatile organic compounds [1]	TRL3[2]	- Purification - Concentration - Separation
Applications with solar integration	- Seawater/brackish water desalination [1]	TRL 3[2]	- Purification

[1](P. Wang & Chung, 2015) and Zaragoza (p.c. 06.04.2018), [2](p.c. Koschikowski, J., 10.04.2018 and p.c. Zaragoza, G., 06.04.2018)

6.3.4. Oscillatory baffled reactors

Working principle, advantages over conventional technologies and underlying PI concept

Oscillatory baffled reactors refer to continuous plug flow reactors with baffles and oscillatory motions being induced from 0.5 to 10 Hz. The combination of baffles and oscillatory motions leads to a formation of vortices below the baffles. The vortices dissolve with every new upstroke of the piston and new vortices are formed (Figure 11) (Reay et al., 2013).

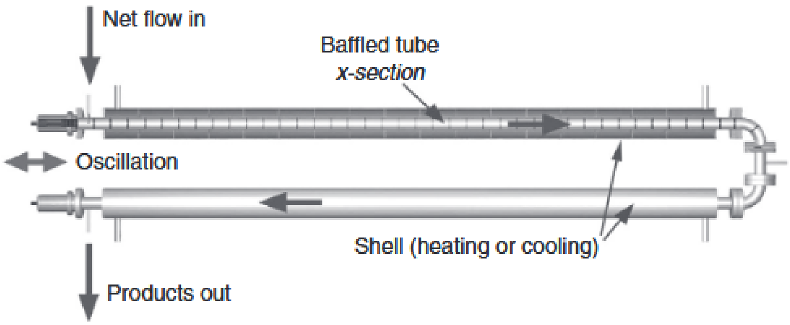


Figure 11 Working principle of an oscillatory baffled reactor (Reay et al., 2013)

There are several advantages of such a reactor. First of all, the creation and the collapse of vortices form an area of high heat and mass transfer. Moreover, the degree of mixing in oscillatory baffled reactors is not dependent on the net flow velocity, and therefore ideal for reactions with a long residence time (above 10 minutes). Moreover, OBR's are easily scalable to a bigger size and can be run in a continuous manner, potentially replacing batch stirred tank reactors (Reay et al., 2013).

Applications

Oscillatory baffled reactors have a broad field of applications, such as food/drinks, pharmaceutical API's and biofuels (Table 17). As the mixing of OBR's is uniform, it is especially suitable for shear-sensitive material as pharmaceutical crystals and flocculates. For this reason, OBR's could also be employed as bioreactors for long processes. Moreover, solid suspension and crystallization are application areas (Reay et al., 2013). The main distributor for OBR's is NiTech, which states several operations as their commercial application field. However, applications are most promising for niche applications (Creative Energy, 2007). For this reason, the multiplicativity is rated with 2.

Table 17 Application areas and development status of oscillatory baffled reactors

Solar integration	Application	Development status	Unit operations
Applications without solar integration	- Hydrogenation [4] - Enzymatic reactions [4] - Polymerization [4] - Transesterification [4] - Nitration [4] - Oxidation [4] - Crystallization [4]	TRL 9	- Mixing
	- Crystallization[3] - Polymerization[6] - Mesoscale OBR's[2] - Solid suspension [5] - Bioreactors[5]	TRL 4	- Mixing
	- API'S[1]	TRL 7	- Mixing

[1](NiTech Solutions Ltd, 2017a), [2](Boodhoo & Harvey, 2013), (Harvey & Phan, 2017), [3](C. Brown et al., 2015), [4](NiTech Solutions Ltd, 2017b), [5](Reay et al., 2013), [6](Lobry et al., 2015; Xiongwei Ni et al., 2002)

6.3.6. Pulse combustion drying

Working principle, advantages over conventional technologies and underlying PI concept

Pulse combustion drying (PCD) is based on the intermittent combustion of solid/liquid or gaseous fuel in the combustion chamber. Pulse combustion induces an oscillatory momentum transfer creating intensive pressure, velocity and temperature waves, which are transported along the tailpipe to the dryer for atomizing and drying (Zbicinski, 2002) (Figure 12). These cycles are repeated at a certain frequency, depending on the design of the combustor, normally at around 20 to 250 Hz.

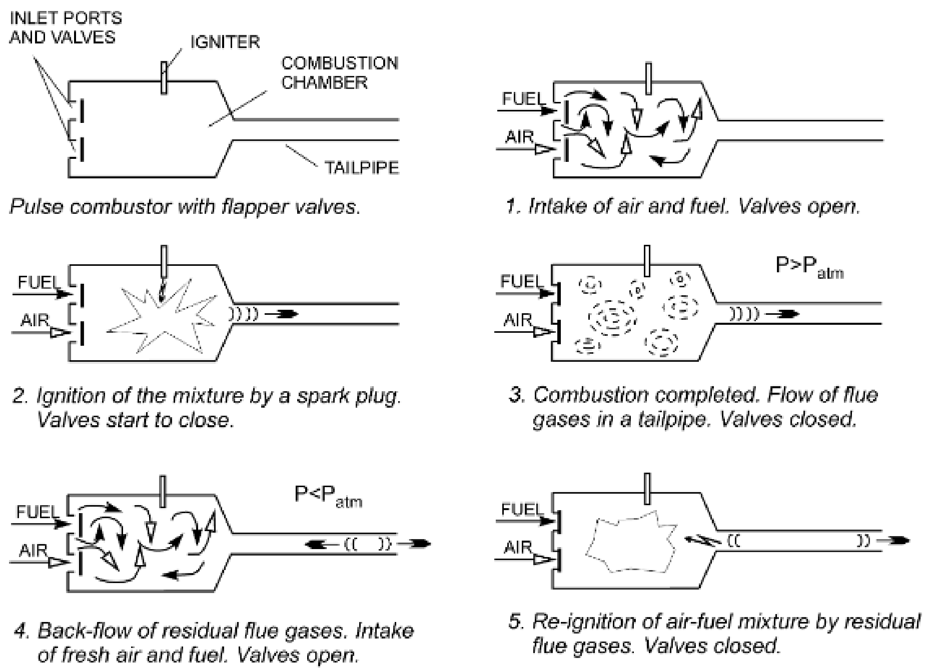


Figure 12 Working principle of pulse combustion (Kudra, 2008; Zbicinski et al., 2014)

Pulse combustion drying increases the heat and mass transfer rates by a factor of two to five compared to continuous combustion. Moreover, the combustion intensity is increased by a factor of 10 and higher combustion and thermal efficiencies can be reached. Pollutant emissions (NO_x, CO_2, and soot) are decreased, whereas the reduction of NO_x is especially advantageous for the drying of food and biomaterials. Furthermore, combustion equipment can be reduced. Improved quality due to the elimination of property distribution (e.g temperature) in the dryer, lower gas and product temperatures and lower air consumption due to the high driving force are other benefits. In general, the energy consumption and drying time are reduced and a wide variety of different materials can be dried (Kudra, 2008).

Applications

Pulse combustion has mainly been employed in spray dryers, but flash dryers, rotary dryers and to a lesser extent fluidized bed dryers also pose options. It could likewise be applied in other drying techniques such as impinging streams, drying in spouted beds and conveyor belt drying (Mujumdar, 2015). Over 150 raw materials have been found suitable for pulse combustion drying. In general, PCD is mostly employed in agri-food, large volume and specialty chemicals and semi-solid wastes drying (Kudra, 2008). Future applications will be the drying of waste sludge where microbial components have to be removed (Mujumdar, 2015) (Table 18). Based on the found application PCD is a really promising technology to intensify drying, especially if the energy-intensive nature of drying is considered. For that reason, multiplicativity is rated with 4 out of 5 points.

Table 18 Application areas and development status for pulse combustion drying

Solar integration	Application	Development status	Unit operations
Applications without solar integration	- Drying of various materials	TRL 9	-Drying -Atomization
Applications with solar integration	- Whey powder[1]	TRL 2	-Drying -Atomization

[1](Brunner et al., 2011)

6.3.7.Microchannel reactors

Working principle, advantages over conventional technologies and underlying PI concept

Microchannels reactors refer to reactors with an extremely small channel size in the order of micrometers to a few millimeters and a channel length of a few cm to several meters (Önsan & Avci, 2016; Reay et al., 2013). Microchannel reactors come with several benefits, the most obvious one being size reduction. Moreover, microreactors have an excellent heat transfer rate due to the high surface to volume ratio leading to good temperature control (1MW/m^3/K). The precise control of the residence time results in high conversion rates and the prevention of by-products during continuous operation. The combination of increased mass and heat transfer also lead to a higher yield. Microchannel reactors are operated in a continuous manner and could, therefore, be an alternative to several batch processes. Microchannel reactors also come with good mixing properties due to diffusion. This is significant in small-scale designs and makes processes easier controllable. Theoretically, scale-up of microchannel reactors is relatively easy, solely by increasing the number of reactors (Kołtuniewicz, 2014).

Applications

Micro-reactors are employed, where accuracy and precision are more important than productivity. Hence, the pharmaceutical field, cosmetics, polymers, the fine chemical industry and the production of analytical reagents are suitable application areas. Green organic chemistry is another promising domain. Moreover, difficult fast exothermic reactions, like nitration, are another suitable operational area due to the good reaction control (Kołtuniewicz, 2014). Solar integration has also been demonstrated in the case of solar methane steam reforming (Drost et al., 2012) (Table 19). This analysis shows the wide application area of microchannel reactors; however, due to the limited throughput multiplicativity is rated with two points.

Table 19 Application areas and development status of microchannel reactors

Solar integration	Application	Development status	Unit operation
Application without solar integration	- Pharmaceuticals, polymers, fine chemical industry and analytical reagents[2]	TRL 9	-Hydrogenation -Dehydrogenation -Oxidation -Synthesis
Application with solar integration	- Solar receivers[1]	TRL 5	– Steam reforming

[1](Drost et al., 2012), [2](Kołtuniewicz, 2014)

6.3.8. Solar furnaces

Working principle, advantages over conventional technology and underlying PI concept

Figure 13b visualizes the working principle of a solar furnace. Heliostats are placed in such a way that they reflect the solar radiation onto a concentrator. The concentrator, which can be a parabolic mirror or several spherical mirrors, bundles the radiation onto the focal point. Additional shutters allow regulating the solar irradiation (Roldán Serrano, 2017).

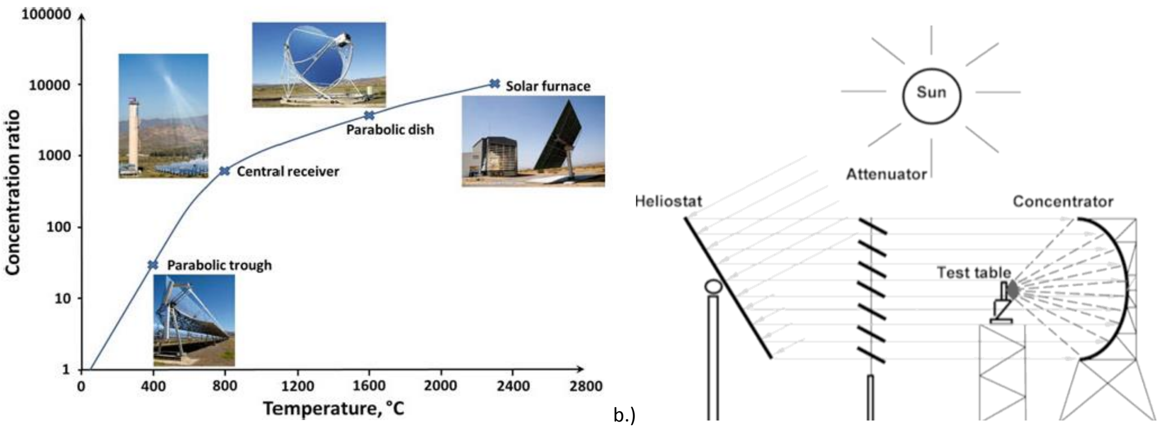


Figure 13 Concentration ratios and temperature profiles of CSP technologies (Roldán Serrano, 2017) and visualization of the working principle of solar furnaces (Oliveira et al., 2016)

Compared to other concentrating power technologies, solar furnaces reach higher concentration ratios and therefore higher temperatures, which allows the utilization of solar furnaces for high-temperature processes.

Applications

Several application areas of solar furnaces have been explored. They are characterized by highly energy-intensive processes with high-temperature requirements (Table 20). Solar fuels are especially of interest as they would allow storage and transportation of solar energy in the form of hydrogen or syngas. Solar furnaces will not be deployed in many different locations; however, the impact can still be quite significant, as the specific applications are widely-used and energy-intensive. For this reason, multiplicativity is assigned 2 points, as only the southern part of Europe (Spain, southern Italy, southern France, Greece, Cyprus, and Malta) can be considered a feasible location with sufficient solar irradiation. The development status of solar furnaces is quite evolved and is mostly limited by the development status of the specific application. For this reason, it is assigned 5 points (p.c. with Flamant, G., 05.04.2018).

Table 20 Application areas and development status of solar furnaces

Solar integration	Application	Development status	Unit operations
Based on solar	- Solar metallurgy (zinc, magnesium, aluminum, silicon) [3]	TRL 4 [1]	- Carbothermic reduction from oxide ores
	- Solar lime [4]	TRL 4 [1]	- Calcination
	- Solar glass production[7]	TRL 4 [1]	- Melting
	- Ammonia[6]	TRL 4	
	- Solar fuels[5] - decarbonization	TRL 5[1]	- Steam reforming/gasification - Storage
	- Solar fuels – water splitting[5]	TRL 3[2]	- Water splitting
	- Research on advanced materials and receiver designs		- Research activities

[1](p.c. with Patil, V., 04.04.2018), [2](IEA, 2010), [3](DLR, 2017; Epstein et al., 2008; Hischier et al., 2015;Wieckert et al., 2007), [4](Meier et al., 2006, 2005), [5](Chaudhary, 2017; IEA, 2010; Konstandopoulos et al., 2012; Steinfeld, 2005), [6](Gálvez et al., 2009), [7](Ahmad et al., 2014)

6.3.9.Solar particle technology

Working principle, advantages over conventional technology and underlying PI concept

This chapter discusses the concept of particles as a heat transfer medium (HTM). Both the potential particle receiver designs and adequate heat exchangers for this technology are explored as these are the components which are lacking maturity in a particle-based power plant (Figure 14). The technology aims at replacing molten salts as a heat transfer medium in concentrating solar power (CSP) plants as molten salts come with severe disadvantages. Firstly, the temperature range is limited to 565°C and significant efforts have to be made to avoid solidification at a temperature below 220°C. Corrosion poses also a problem and costs are quite high. In contrast, using particles as the heat transfer medium supports higher temperatures, corrosion is not an issue and it is relatively cost-efficient. Moreover, solid particles could also be used for thermal storage (Gomez-Garcia et al., 2017; Ma et al., 2015). Ceramics are well suited for the utilization in direct receivers and are therefore mostly employed, while sand, due to the low absorptivity is better suited for indirect receivers with the huge advantage of very low costs (Mehos et al., 2017).

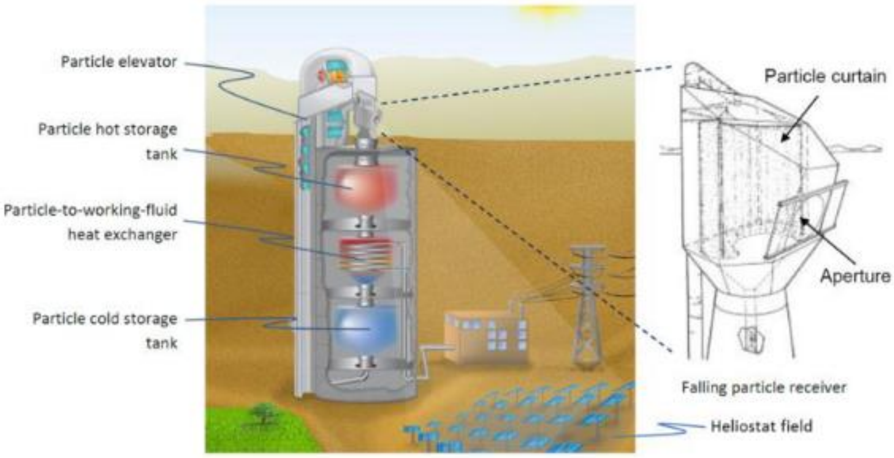


Figure 14 Particle-based power plant with a falling particle receiver system (C. Ho et al., 2013)

There are several designs for receivers with one specifically designed for industrial process heat applications: the packed particle receiver (p.c. Johnson, E., 13.04.2018). Also, various designs (fluidized bed HX, shell and tube HX or shell and plate HX) have been developed.

Applications
Currently, there are no commercial applications or demonstration projects for a solar particles plant. One project is planned in Saudi Arabia for a commercial particle receiver for electricity production, where final prototype testing should be finished in 2019 (Kraemer, 2018). Electricity production poses one quite intensively researched area, but particle technology could also find application in thermochemical storage and solar fuels and in industrial processes with a temperature demand of about 1000°C (C. Ho et al., 2013). One example for an industrial application area is the calcination of lime in the cement production. Moreover, solar particle technology could be employed in metallurgical processes for heating metals and for preheating gases.

Solar integration	Application	Development status	Unit operations
Based on solar	Cement production [1]	TRL 2	- Calcination
	Metallurgical processes [1]	TRL 2	- Heating
	Pre-heating of gases [1]	TRL 2	- Melting

[1] (p.c. Johnson, E., 13.04.2018)

6.4. Current issues of emerging technologies

In this chapter, the current issues of emerging technologies are discussed. These obstacles can stem from technical issues, integration problems, costs, location constraints to market barriers. These are analyzed with the aim to identify the limitations in the overall potential of emerging technologies to facilitate the integration of solar heat in industrial processes, which will be later used in the potential analysis. Based on these barriers, future actions which have to be undertaken can be identified.

As shown in Table 21 most of the identified barriers of process technologies refer to technical challenges. This might be due to the naturally early development stage of emerging technologies. This is also reflected in the way the potential is limited, which is the development status and the criteria multiplicativity if the technical issue limits the application area. Moreover, current processes might not be designed to integrate emerging technologies. In case of pulse combustion drying the utilization of fossil fuels was mentioned as an issue, and research regarding renewable options was emphasized. Moreover, market barriers are in place in the case of membrane separation. Koschikowski mentions a lack of engagement of membrane producers due to a lack of trust in a future uptake of membrane distillation. Industries are only interested in new technologies if they reduce costs significantly or are induced by policy requirements. This underlines the need for demonstration projects which are currently not in place (p.c. with Koschikowski, J., 10.04.2010). Interestingly, high energy consumption is also mentioned as a current barrier in membrane distillation. The high energy requirements are also identified by the US EIA, stating that 16% of the total consumed energy is for separation processes, whereof 50% are carried out by distillation; it is estimated that up to 90% of energy could be saved by membrane-based separation. While this study aims at phasing out heat driven separation processes in total, it is yet to be mentioned that a combined approach of membranes and heat driven distillation could be a feasible option, leading to reduced energy consumption (Sholl & Lively, 2016). This underlines the potential membrane distillation and pervaporation offer to reduce energy consumption and stresses the fact that they could play an important role as future separation methods.

Table 21 Current barriers of emerging process technologies

Technology/Principle	Application Issue	Barrier	Limiting potential in what way
Extended heat exchange surfaces	Unsuitable current process design [1]	Integration in current processes	Development status, Integration in industrial processes
	Significant pressure drop, restricting the scope of application [2]	Technical challenge	Multiplicativity
Pervaporation	Need for high-performance membranes [3]	Technical challenge	Development status
	Small water flux [3]	Technical challenge	Multiplicativity, Development status
Membrane distillation	Design of membranes and modules [5]	Technical challenge	Development status
	Pore wetting and fouling [5]	Technical challenge	Development status, quality of the product, efficiency
	Low permeate flow rate and flux decay [5]	Technical challenge	Development status, Multiplicativity
	High energy consumption [6]	Technical challenge/costs	Costs, Multiplicativity
	Lack of engagement of membrane producers and industry [7]	Market barrier	Development status
	No long-term demonstration projects [7]	Market barrier, costs, technical challenge	Development status, Multiplicativity
Oscillatory baffled reactor	Robustness [4]	Technical challenge	Development status
	Cross-contamination [4]		
	High density and high viscosity liquids [4]		
Pulse combustion drying	No clear understanding of the interaction of the sonic wave with the	Technical challenge	Multiplicativity, Development status

	drying chamber and the material[8]		
	No active control over combustion parameters[9]	Technical challenge	Development status, efficiency
	Utilization of fossil fuels[9]	Technical challenge	Long-term consideration
	Severe noise[10]	Technical challenge	Multiplicativity, integration in current processes
Microchannel reactors	Small throughput[11]	Technical challenge	Multiplicativity
	High-pressure drop[12]		Efficiency
	Clogging [12]		

[1](Muster & Brunner, 2015), [2](Tiwari et al., 2016), [3](Q. Wang et al., 2016), [4](X. Ni, n.d.), [5](El-Bourawi et al., 2006), [6](P. Wang & Chung, 2015) and (p.c. Koschikowski, J., 10.04.2018), [7](p.c. Koschikowski, J., 10.04.2018),[8](Mujumdar, 2015), [9](Kudra, 2008), [10](Zbicinski et al., 2014), [11](Hessel, 2008), [12](Creative Energy, 2007)

For supply technologies, sufficient solar radiation certainly is a premise. Figure 15 visualizes areas with a solar irradiation of above 2000 kWh/m^2 and therefore a reasonable suitability for CSP technologies. All in all, suitable locations are often found in latitudes from 15° to 40° North and South due to clouded conditions at latitudes closer to the equator. Also, higher altitudes are good CSP locations, as absorption and scattering of sunlight are lower. For this reason, the quantitative potential of electricity production is estimated to be the highest in North America, Africa, and India, with Europe being the smallest producer but largest importer (IEA, 2010). This confirms the limited potential of solar process heat from CSP in the EU.

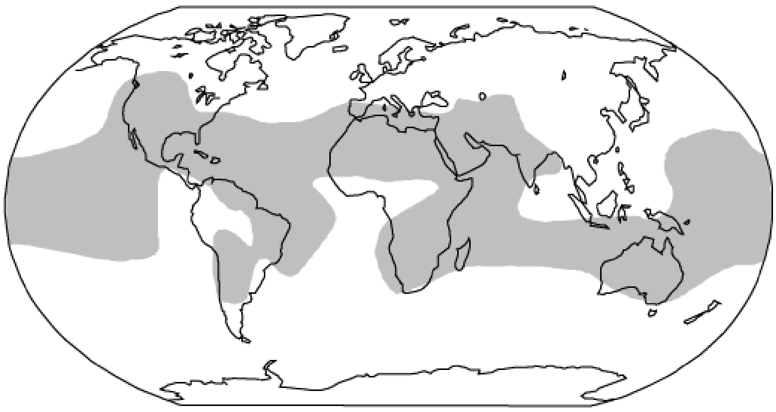


Figure 15 Areas with an annular solar irradiation above 2000kWh/m^2 (Meier et al., 2005)

Moreover, the high amount of costs for such a plant leads to high production costs, which needs to be reduced in order to become economically feasible, unless fossil fuel prices go up, which would consequently push up prices in the conventional production route. In case of the solar particle technology, barriers are mostly of technical origin, hampering the efficiency and the development of the technology. As the technology is not yet well developed, system modeling is currently an issue. For solar furnaces, the principle technology is already quite developed, while the technology for specific applications is in need of further research (Table 22).

Table 22 Current barriers of emerging supply technologies

Technology/Principle	Application Issue	Barrier	Limiting potential in what way
Solar furnaces	Solar irradiation [1]	Location	Multiplicativity

	Higher production costs[3]	Costs	Costs
	High installment costs[2]		
	Temperature resistant materials for reactor[2]	Technical challenge	Multiplicativity
	Specific applications need to be further developed, not so much the concept of SF	Technical challenge	Multiplicativity
	Continuous operation[2]	Batch production	Multiplicativity, integration in current processes
Solar particle technology	Particle loss[4]	Technical challenge	Efficiency
	Need for high efficiency receivers[4]		Efficiency
	Information on thermal and mechanical properties of particles[5]		Development status, efficiency
	System modelling[4,5]		Development status
	Scale up[6]		Development status, Multiplicativity
	Moving bed HX spacing/sizing of tubes, flow stagnation and shadow below tubes [4,7]		Development status, efficiency

[1](Meier et al., 2005), [2](Villafán-Vidales et al., 2017), [3](Meier et al., 2006), [4](Mehos et al., 2017), [5] (p.c. Johnson, E., 13.04.2018), [6](p.c. Flammant, G., 05.04.2018), [7](C. K. Ho, 2016)

In general, technical challenges are identified as the main barriers of emerging technologies, which could be explained by the premature state of development with market and economic barriers not yet having been identified. Technologies which are already further developed mention costs as the main limitation.

6.5. Enabling factors for solar process heat in industrial processes

This chapter explores the factors which facilitate solar integration by emerging technology compared to the conventional technology. These benefits are related to the previously identified barriers and bottlenecks (Table 23). It can be concluded that there are several principles, which are beneficial for solar integration. These strategies can be employed in different ways in the specific technology. One example is a higher heat flow, which could reduce the temperature demand and, therefore, enable solar integration. The increase of the heat flow can stem from an extended surface or the appliance of oscillatory motions and therefore the formation of vortices, increasing the heat transfer coefficient (Figure 16). Moreover, a change in the process can entail lower temperatures, as in the case of pervaporation and membrane distillation (Figure 17).

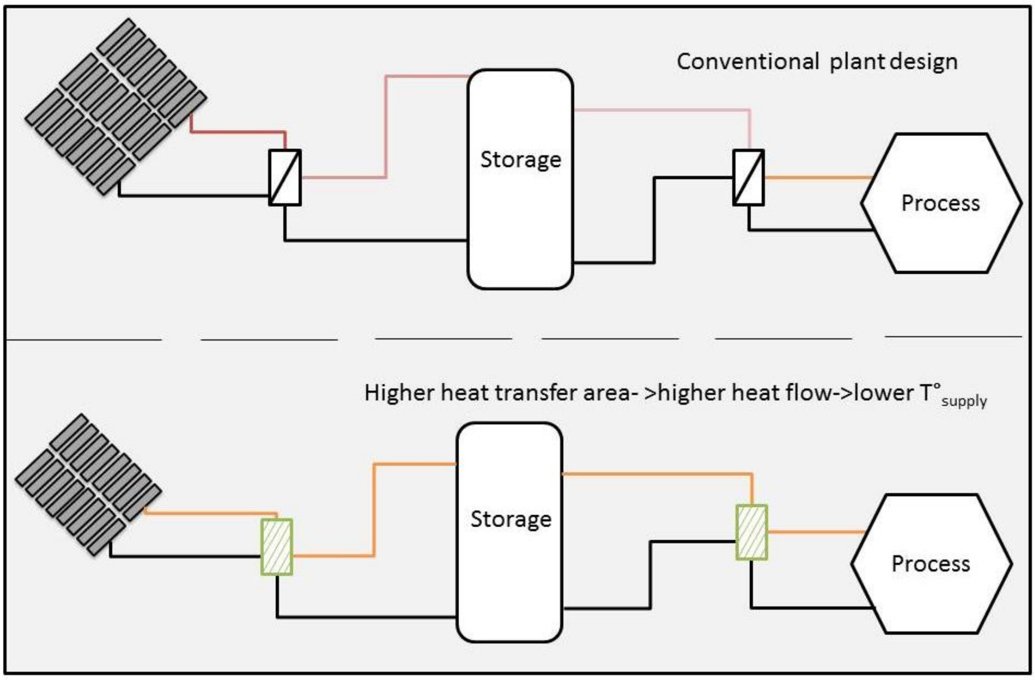


Figure 16 Benefits of a higher heat flow, in this case, due to an extended heat transfer surface

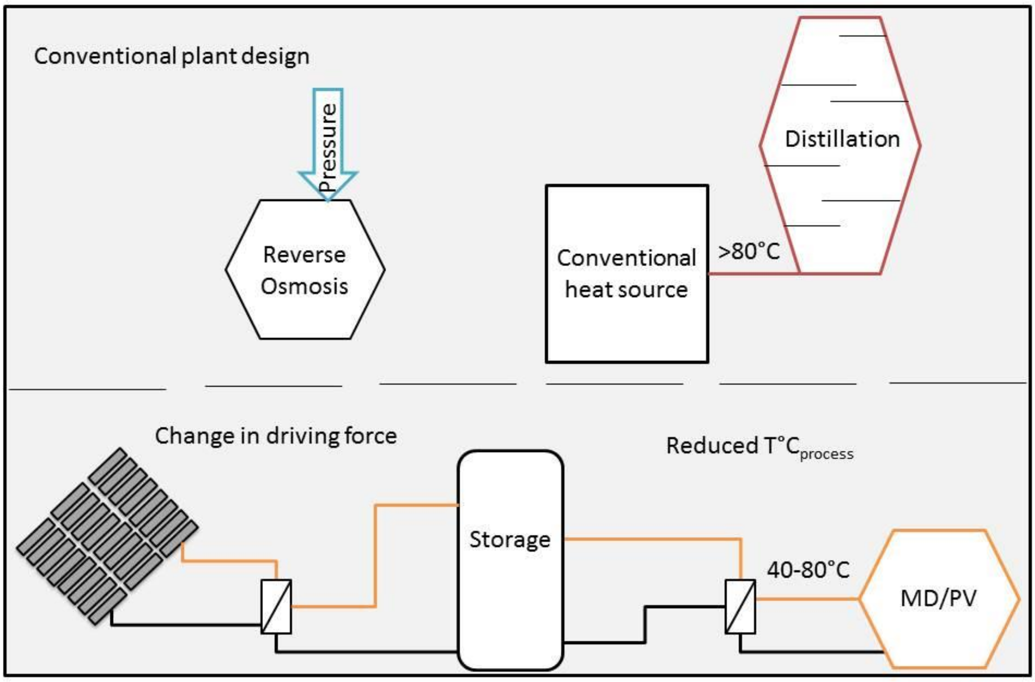


Figure 17 Benefits of a change in the process design in the case of pervaporation and MD

Furthermore, an increased efficiency is favorable for process intensification. An increased efficiency could lead to both a higher covered solar fraction and a reduction in costs. While the availability of solar radiation was found to be a barrier, in the case of desalination it could be regarded an enhancing factor, since water scarcity is mostly an issue in areas with high solar irradiation. Moreover, a switch from batch to continuous processing would address the issue of varying process loads, which would also benefit solar integration by eliminating a high peak demand and reducing equipment size, as in the case of oscillatory baffled reactors and microchannel reactors (Figure 18).

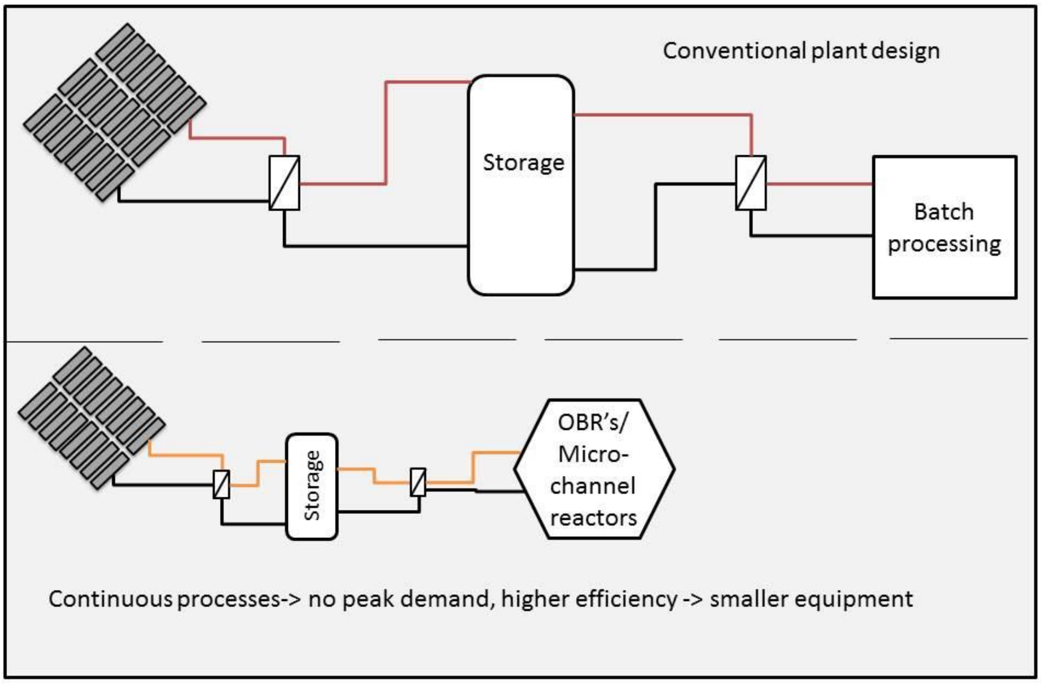


Figure 18 Benefits of a switch from batch to continuous processing for OBR's and microchannel reactors

Interestingly, the opposite is stated in the case of membrane distillation, where the possibility to run the process in a discontinuous manner was mentioned as a benefit for solar integration due to a reduced need for storage and the utilization of a higher degree of solar irradiation.

While the benefits of emerging process-based technologies often lie in the reduction of the required temperature, solar supply technologies can address this issue by enabling higher temperatures. Figure 19 visualizes the concept for solar particles as a heat transfer medium, but this is also true for solar furnaces.

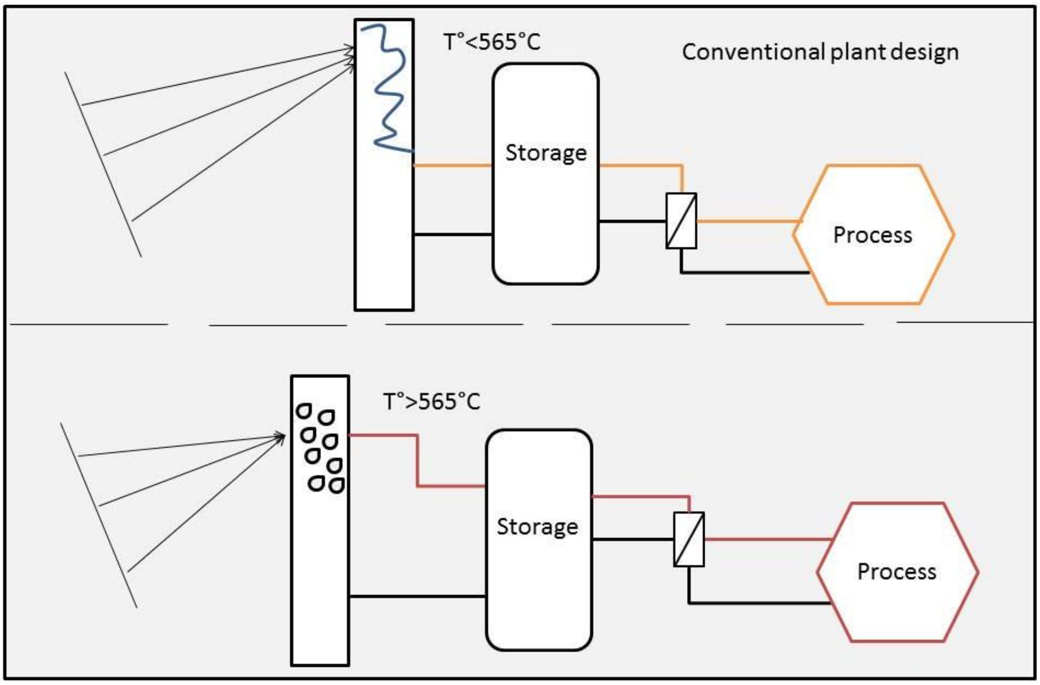


Figure 19 Benefits of particles as a heat transfer medium

The issue of solar availability can be avoided if solar energy can be effectively stored and transported. For this reason, storage as solar fuels (hydrogen/syngas) is really promising (Figure 20).

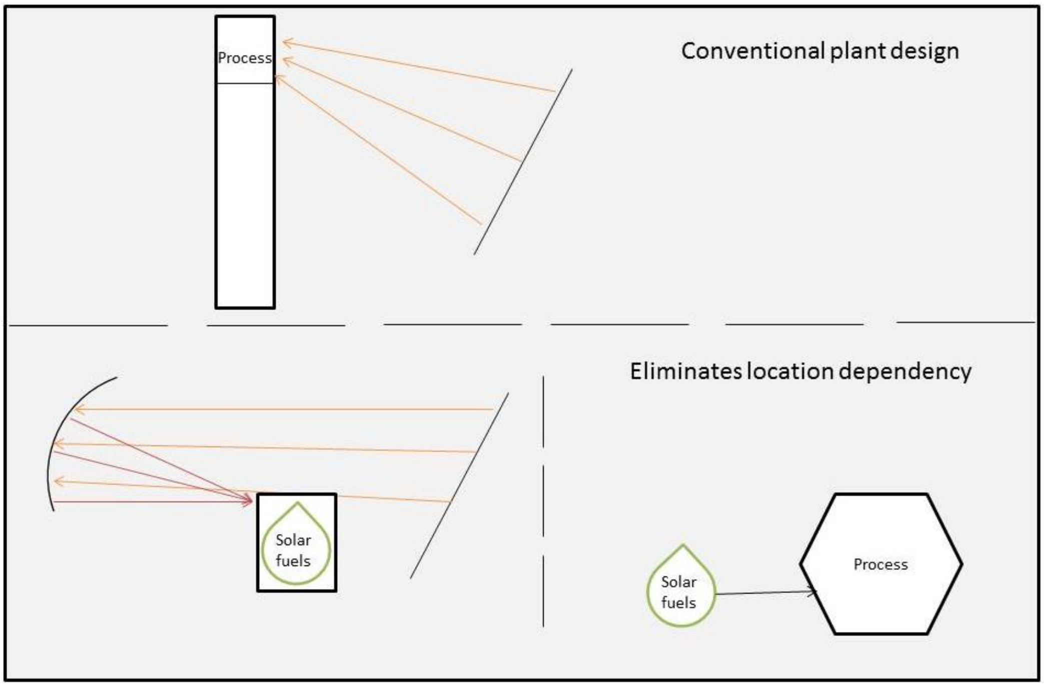


Figure 20 Benefits of solar fuels

The possibility of direct storage is also an advantage of solar particles as a heat transfer medium. Moreover, it should be stated that the CSP technology is an intensively researched area. While most attention has been paid to electricity generation, the IEA also recognizes process heat as a promising application area. There are several estimations concerning the production of electricity from CSP. All in all, it is estimated that CSP could save 560 million tons of CO_2 due to natural gas savings from solar fuels according to the ETP baseline scenario. It is further estimated that solar or solar enhanced gaseous or liquid fuels will become commercially feasible by 2030 and moreover, substitute 3% of the global natural gas consumption and almost 3% of the global consumption of liquid fuels by 2050 (IEA, 2010). This underlines the focus that has been put on CSP technologies in general. While this mostly refers to electricity production, it is also a really promising outlook for solar process heat as the technology will become more mature and cheaper.

Table 23 Enabling factors for solar integration in industrial processes

Technology	Benefit	Barriers addressed
Extended heat exchange surface	Higher heat transfer coefficient[4]	High-temperature demand
	Efficiency gains[4]	High costs
Pervaporation	Works with low temperatures[1]	High-temperature demand
	Water scarcity often occurs in areas with high solar irradiation[2]	Solar availability
Membrane distillation	Low-temperature demand[8]	High-temperature demand
	High efficiency of solar collectors at temperatures from 50°C-80°C, which is required for MD[9]	Efficiency losses due to high-temperature demand
	Operation in a discontinuous	Storage

	manner[10]	
Oscillatory baffled reactor	Higher heat transfer coefficient[3]	High-temperature demand
	Continuous reactions possible[5]	Varying process loads
Pulse combustion drying	Increased heat transfer [14]	Need for high-temperature supply
Microchannel reactors	Higher heat transfer coefficient[13]	High-temperature demand
	Continuous reactions possible[13]	Varying process loads
Solar furnaces	Higher temperature[7]	High-temperature demand
	Energy Storage by the means of solar fuels[6]	Solar availability
Solar particle technology	Higher temperatures[11]	High-temperature demand
	Direct energy storage in particles[12]	Solar availability

[1](Xie et al., 2014)' [2](Zwijnenberg et al., 2005)' [3](Muster & Brunner, 2015)' [4](Bergman et al., 2011)' [5](Reay et al., 2013)' [6](Chaudhary, 2017)' [7](Roldán Serrano, 2017)' [8](El-Bourawi et al., 2006), [9](Blanco Gálvez et al., 2009)' [10](p.c. Koschikowski, J., 10.04.2018 and Zaragoza, G., 06.04.2018), [11](Gomez-Garcia et al., 2017; Ma et al., 2015), [12](Gomez-Garcia et al., 2017),[13](Kołtuniewicz, 2014), [14](Meng et al., 2016)

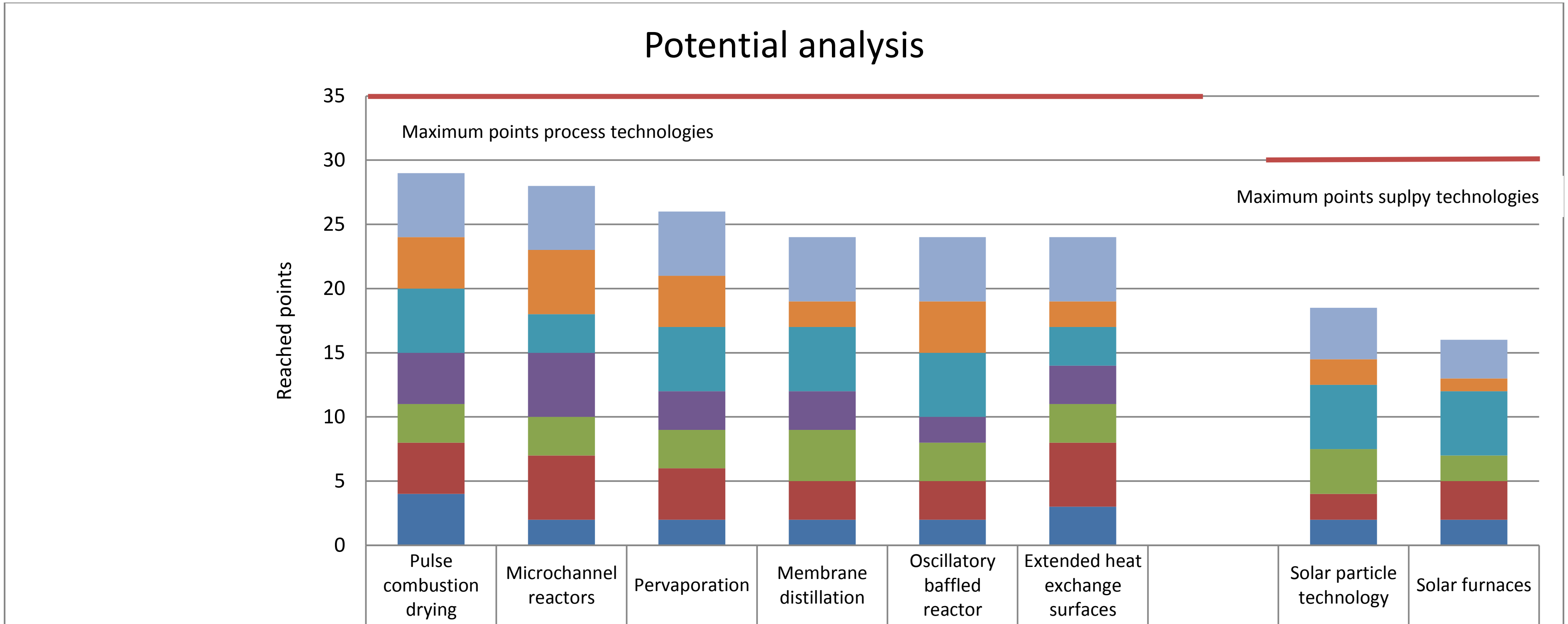
7. Potential analysis

This chapter analyses the potential of each technology based on the previous analysis, interviews and literature sources according to the selected criteria. The outcome of the questionnaire regarding the weighting of criteria did not lead to a satisfactory conclusion as the answers varied significantly. It seems that there is no clear consensus on criteria associated with a higher impact and criteria with a lower impact on the overall potential. Hence, all criteria are expected to have the same influence on the potential. Figure 21 visualizes the assigned points and ratings. It has to be considered that for process technologies, displayed on the left side, the maximum points were 35, while supply technologies could only reach 30 points, due to the absence of the criteria solar integration. Appendix E presents the detailed rating and reasoning of the criteria for each technology.

First of all, some general conclusion regarding the criteria can be drawn. The criterion efficiency is rated superior to the conventional technologies for all process technologies. This is not surprising since the technologies are specially designed to intensify processes, where a higher efficiency is a key element. Moreover, a higher quality of the products for example due to a higher selectivity of the process is indicated. For the solar particle technology, a higher efficiency was also stated compared to the conventionally used molten salt as a heat transfer medium, while for solar furnaces efficiency gains are not considered a main benefit of the technology. The key advantage of solar furnaces is a higher temperature supply. Therefore, the quality of supply technologies is superior, since the temperature range is the decisive factor for the criterion quality for supply technologies. Benefits for solar integration are naturally present for all technologies, as this was the decisive factor for selecting the technologies in the first place. The integration of the technology in the current process was estimated feasible but to cause minor adjustments for all the process technologies. This holds also true in case solar particles are used as a heat transfer medium, which could replace the HTF medium in an existing plant with several changes in the process design. For solar furnaces an entire system has to be built, requiring a lot of effort. This also explains the issue of costs for supply technologies. The technologies have been proven to work in demonstration projects, while some have already been commercially employed. Only the solar particle technology is still tested on a laboratory scale. The development status differs for the technologies. For some, research on an experimental basis is still necessary, while others are already quite advanced and solar integration could be tested.

Secondly, the main properties of the particular technologies are introduced. Pulse combustion drying has scored the highest in this analysis. One key factor for that is the good rating of the criterion multiplicativity, due to the fact that drying is a widely used and energy-intensive process. Moreover, the quality and efficiency are increased because of the elimination of property distribution and costs are lower than in conventional combustors due to the compact sizing. It has to be considered that solar heat is used to pre-heat the feed or combustion air and does not eliminate the current need for fuel input but reduces it. Microchannel reactors are also ranked well and are mostly limited in the criterion multiplicativity due to the restricted throughput; however, microchannel reactors have been employed in several industrial processes where precise regulation conditions are more important than a large output. Pervaporation is ranked highly for the quality of the product due to increased separation ability, leading to highly concentrated products. Solar integration is promising especially for desalination, however, similar to microchannel reactors the currently really low flux only allows for small quantities to be processed, which limits the criterion multiplicativity. For some applications, pervaporation has been applied in industrial processes and cost-effectiveness has also been proven. Membrane distillation comes with similar benefits as pervaporation, however, costs are estimated to be higher and no commercial applications exist. Oscillatory baffled reactors are known for their good mixing characteristics in slow reactions. These are also the main application areas of OBR’s, which are, however, mostly niche applications, reducing the factor multiplicativity. Moreover, solar integration has not yet been researched. Extended heat exchange surfaces are ranked highly in the category development status since they have already been employed widely in industry. The application area is wide-spread, however, extended heat exchange surfaces are mostly employed in small installations, which limits the criterion multiplicativity but also the criterion easiness to integrate the technology.

On the supply side, higher temperatures can be reached by solar furnaces and solar particle technology. The main barrier is the associated high costs, which also hamper the development status. In the case of solar furnaces, the development status is limited by the development of the applications such as solar reactors, and not by the design of the solar furnace itself. Moreover, location constraints due to the availability of solar irradiation are an issue on the supply side, which reduces the criterion multiplicativity.



	Pulse combustion drying	Microchannel reactors	Pervaporation	Membrane distillation	Oscillatory baffled reactor	Extended heat exchange surfaces		Solar particle technology	Solar furnaces
Efficiency	5	5	5	5	5	5		4	3
Costs	4	5	4	2	4	2		2	1
Quality	5	3	5	5	5	3		5	5
Solar integration	4	5	3	3	2	3			
Easiness to integrate the technology	3	3	3	4	3	3		3.5	2
Development status	4	5	4	3	3	5		2	3
Multiplicativity	4	2	2	2	2	3		2	2

Figure 21 Potential analysis

Based on these results it is argued that the technologies are not only suitable to overcome current barriers to solar integration but are also in other aspects promising alternatives. Generally, process technologies are ranked well on almost all indicators. Especially pulse combustion drying and microchannel reactors are really promising technologies, not only for solar integration but also in regard to other parameters. On a supply-side fewer points were reached mostly due to a lack of high solar irradiation in central and northern Europe and the associated high costs of these technologies; however, especially the production of solar fuels is a really interesting route, as it eliminates the location dependency of CSP plants. It is important to notice that these technologies are not competing with each other, as all come with their own application area as shown in Table 24. Only membrane distillation and pervaporation have related unit operations but come with their own application areas. Several technologies could also be combined, as for example in distillation-pervaporation systems enhancing the efficiency of the process and potentially solar integration. It is also possible that one principle/technology is employed in another, such as extended heat exchange surfaces in microchannel reactors. Especially, supply and process technologies are not comparable and should be regarded in a combined system as for example microchannel reactors and solar furnaces for steam reforming.

Table 24 Application areas of the technologies

	Technology	Unit operations
Process technologies	Extended heat exchange surfaces	Cooling processes Space heating/cooling Drying Mashing Evaporation and distillation
	Pervaporation	Purification Concentration Separation
	Membrane distillation	Purification Concentration Separation
	OBR's	Mixing
	PCD	Drying
	Microchannel reactors	(de)hydrogenation Oxidation Synthesis Steam reforming
Supply technologies	Solar furnaces	Calcination Melting Steam reforming Water splitting Energy storage Carbothermic reduction from oxide ores
	Solar particle technology	Calcination Melting

8. Discussion and limitation

With the objective of answering the main research question and the 5 sub-questions several interviews have been conducted and various literature sources explored. The main sources differ in their aim, conditions, and limitations and are therefore carefully analyzed in this chapter regarding their suitability and reliability to represent the foundation of this research.

8.1. SHIP database

The first sub-question was mainly answered by the means of an analysis of the SHIP database. This database is based on the company's initiative to register implemented projects and provide data. It cannot be expected that each company is acquainted with the database and even if so, provides information. For this reason, an analysis of projects found in literature and their availability in the database was conducted. This was necessary since the obtained data from the platform was used to represent SHIP installation in general and could be misleading if many projects were not included. The results, however, made clear that the database gives a representative overview of the general project type and can, therefore, be used for the analysis.

The economic analysis for the registered projects in the SHIP database was carried out from a company's perspective and therefore a discount rate of 8% was chosen. Figure 22 visualizes the changes in costs for a higher discount rate of 12%. The results show that the costs in €/kWh are still below the conventionally paid fuel price. Subsidies, on the other hand, could reduce the discount rate, as it would reduce the risk companies have to take. Considering that these types of projects might be also of interest from a social perspective the outcome of a 4% discount rate is also shown. Naturally, a lower discount rate reduces the costs even more. For installations with high costs, the discount rate proves to have more influence than for smaller projects.

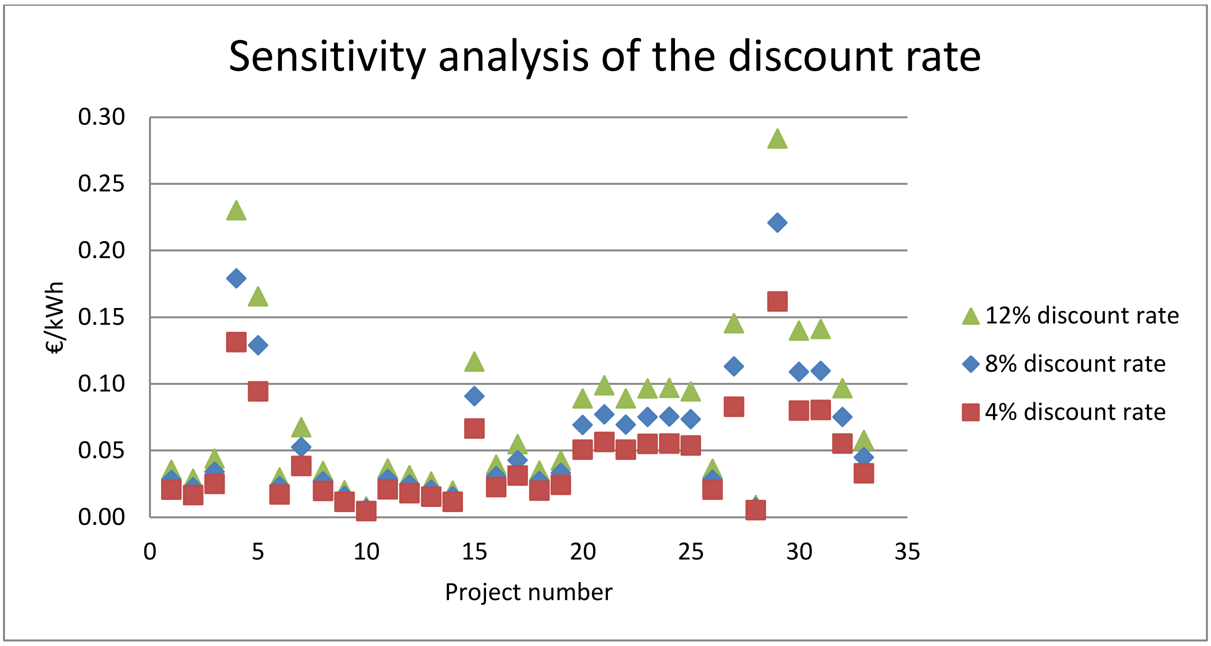


Figure 22 Sensitivity analysis of the economic analysis

8.2. The selection and potential analysis of emerging technologies

The European Roadmap for Process Intensification was used as a major information source for the creation of the roadmap. One the one hand, it was used to provide the structure for the analysis of the emerging technologies and therefore for this paper and on the other hand, the emerging technologies introduced in the roadmap were used for the selection of the emerging technologies which could enhance the integration of solar process heat in industrial processes. The roadmap was already published in 2007 and might therefore not include the latest advances in the technology development or miss certain state-of-the-art discoveries. However, it is the most complete and available document. Moreover, the development status of the technologies was backed up with contemporary literature sources to take recent advances into account. The roadmap focusses on 4 different sectors only: Petchem (petrochemical, bulk chemicals), Finpharm (specialty chemicals, pharmaceuticals), Infood (Food ingredients) and Confood (consumer food). In contrast, this paper takes all industrial sectors into account. For this reason, additional literature was used to identify unit operation and applications, which might be outside of the aforementioned sectors. The scope of the European Roadmap for Process Intensification is the EU, which matches the extent of this paper. For this reason, all assumptions and implications are based on the EU and might therefore not be applicable for regions outside the scope. The obtained general information from the roadmap is considered reliable since the information was given by experts for the respective technology.

The selection of the emerging technologies was based on the potential to overcome identified bottlenecks of solar integration. These bottlenecks were identified in a paper by Muster and Brunner (2015). It is not said that these are overarching, but there might be several characteristics which could also be enhancing for solar integration but have not been considered in the selection process of this paper. Moreover, the rating with X, XX, XXX according to the properties of the technology could be argued to be quite subjective. Nonetheless, the chosen approach is regarded suitable for the goal of selecting promising technologies for solar process heat as the identified technologies have often already been put in context with solar heat.

One crucial part of this paper was the ranking and weighting of criteria. With the aim to objectify these two parameters a questionnaire was conducted. The information gained from the interviews was regarded to be highly reliable, as the interviewees are all considered experts for the specific technology. Nevertheless, the weighting of criteria is still quite subjective to the expert, who might be influenced by the characteristics of the technology he or she is dealing with. The results did not show a clear consensus on certain criteria, which might be more influential than others. Therefore, the weighting turned out to be the main uncertainty of this report. For this reason, no weighting was carried out in the potential analysis. Table 26 and Figure 23 visualize the ranking according to three different scenarios: in one, no weighting of criteria was assumed, in the second a weighting from Brunner et al. (2011) was used and lastly the average of the answers of the questionnaire were regarded. Table 25 presents the weighting of the two different scenarios. The criteria were adjusted to fit the purpose of this study, which might be a liability itself; however, it was the best option to come up with a second and third reasonable weighting.

Table 25 Weighting of the sensitivity analysis

	Brunner et al. [2]	Questionnaire answers[1]
Multiplicativity	0.14	0.11
Development status	0.13	0.14
Easiness to integrate technology	0.16	0.16
Solar integration	0.19	0.16
Quality	0.06	0.14
Efficiency	0.13	0.13
Costs	0.13	0.15

[1]In the questionnaire the criterion quality was not included, for this reason, the average of the other criteria was calculated and this number was used for the criterion quality.

[2] In Brunner et al. O&M cost and installments costs were two separate parameters, which were brought together in this analysis. Moreover, the primary energy consumption in Brunner et al. was used as an indicator of the criterion efficiency and the parameters scale-up was assumed to be an indicator of the development status. For the criterion multiplicativity, the average of the other parameters was chosen. Other mentioned parameters in Brunner and al. were neglected for the purpose of this analysis.

The ranking of the technologies is different for each scenario; however, the aim of this paper was not to rank the different technologies but to analyze their potential for solar integration. The potential for pervaporation, PCD and microchannel reactors is quite promising since they are all ranked well in each scenario. In general, all technologies but solar furnaces are ranked between 60 and 80 points, of a maximum of 100 points, which is a satisfying result for the technologies. Solar furnaces are ranked quite far below all other technologies for each scenario.

Table 26 Sensitivity analysis of the influence of the weighting of parameter

No weighting	Points	Brunner et al.	Rating	Questionnaire answers	
Pulse combustion drying	82	Microchannel reactors	84	Microchannel reactors	76
Microchannel reactors	80	Pervaporation	77	Pulse combustion drying	75
Pervaporation	74	Pulse combustion drying	75	Pervaporation	69
EXHS, MD, OBR	69	Extended heat exchange surfaces	67	Solar particle technology	66
Solar particle technology	62	Oscillatory baffled reactors	63	Membrane distillation	64
Solar furnaces	53	Membrane Distillation	60	Oscillatory baffled reactors	63
		Solar particle technology	60	Extended heat exchange surface	61
		Solar furnaces	52	Solar furnaces	55

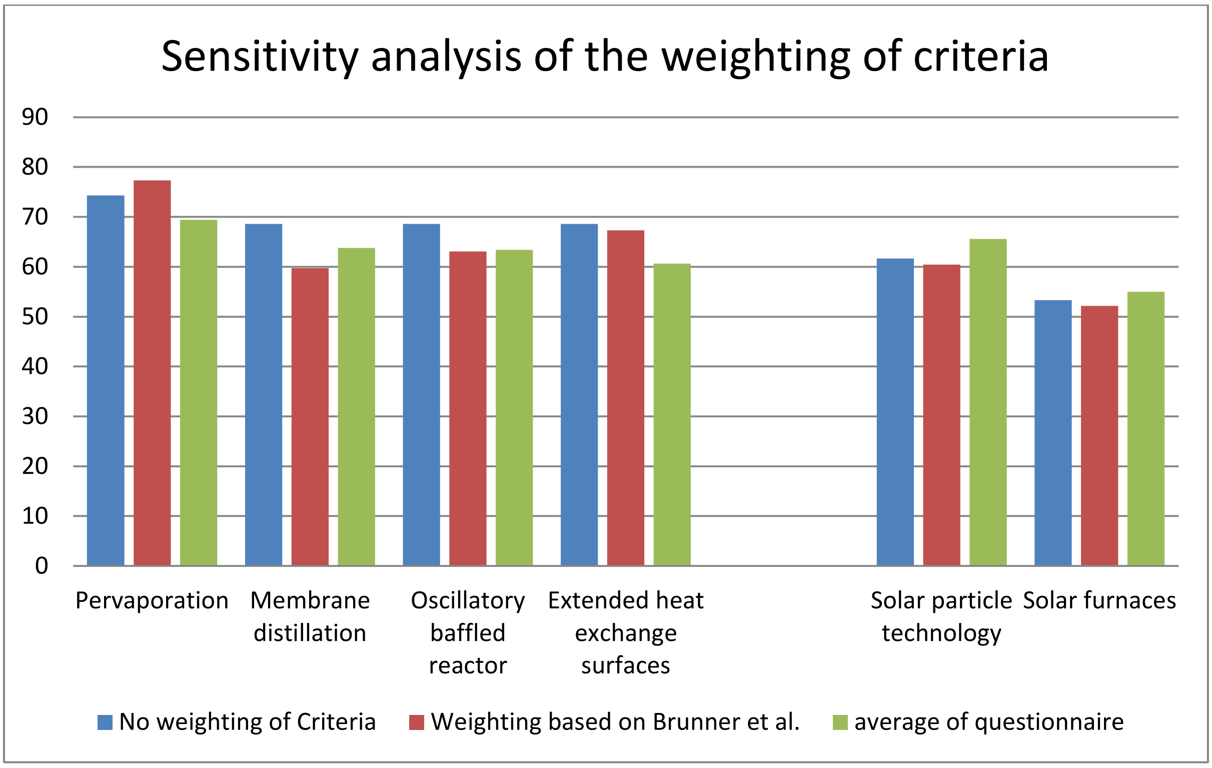


Figure 23 Sensitivity analysis of the weighting of criteria

Another liability was the ranking of criteria. All besides two criteria were based on the questionnaire or on literature sources. However, the development status was rated for each application area itself and differed quite widely, however, in the end, an average was determined for the overall technology for the potential analysis. It is argued that a well-developed application area has a positive influence on the other applications and therefore accelerates the development in the less advanced applications. Moreover, it needs to be considered that the TRL only gives information on the current development status and it does not give an indication of the time span for further development. Secondly, the criterion multiplicativity was assigned on own estimations but backed up with literature sources.

8.3. Limitations and further research

This research analyses the potential of emerging technologies to enhance the integration of solar heat in industrial processes. The analysis is of qualitative manner and therefore solely gives indications of technologies which could enhance the integration of solar process heat. The results do not give information about the quantitative potential. For a few technologies, general quantitative estimations were found in literature, which were used to back up the qualitative results. If the technologies become further developed and more widely deployed, calculations regarding the quantitative potential would be of interest in order to emphasize for example energy savings which could be achieved by solar integration based on emerging technologies.

Testing of the technologies and testing of possible integration options with solar heat was not in the scope of this research. Therefore, barriers which have not been mentioned in literature or were found in the analysis of current SHIP installations might occur with the integration of solar heat.

While several research facilities work on the working principle of the technologies, demonstration plants need to be set up in order to identify issues in real-world settings.

Furthermore, the location was only considered a barrier in case of the supply technologies. Therefore, the availability of solar irradiation has not been regarded for process technologies. This also means that summer and winter variations and effects of day and night alterations were neglected. Moreover, the scope of this research did not include solar heat storage and advances therein which could assist in overcoming barriers especially the previously mentioned variations and is a crucial part in most integration schemes. Solar cooling was also not considered in this paper but could also become valuable for industrial processes. These two topics could pose interesting options in the future. Policies have also not been included in this research but could enable a wider deployment of the technology and solar integration.

This research combines studies on emerging technologies and solar integration in industrial processes. It, therefore, introduces a framework for identifying promising emerging technologies. This framework can be used to evaluate a wide range of process technologies. Moreover, the potential of these technologies was evaluated according to several criteria. These criteria could also be of interest for the evaluation of technologies, not necessarily referring to solar integration, but could also be used for the evaluation of technologies in other fields e.g. wind energy or geothermal energy. Indications about the respective unit operations are also given which could be brought together in future studies with adequate industrial sectors. Moreover, barriers were identified giving indications on necessary policy support in order to enable a wider deployment of the identified technologies for solar process heat. The identified technologies are moreover considered a starting point for promoting emerging technologies due to their general benefits regarding PI and more specifically regarding solar integration.

8. Conclusion and recommendations

This study explored to what extent emerging technologies can expand the potential of solar process heat in the EU. In a first step, a preliminary analysis of current barriers to solar heat in industrial processes and renewable heat supply options was conducted. Secondly, a framework for the selection of promising emerging technologies to facilitate solar process heat was introduced. The selected technologies were evaluated according to certain criteria based on literature sources and a questionnaire. This information was then further used in a potential analysis.

The results of the preliminary assessment showed that numerous renewable alternatives for heat conversion technologies exist, especially for low-temperature demand, such as biomass, geothermal, solar and electricity from renewable sources, whereas solar heat was identified as a really promising renewable heat source as it covers low, medium and also high-temperature supply. However, currently, fossil fuels are the predominant fuel source for heat production (BP, 2017). Yet, there are several projects with solar heat integration. The analysis of these projects identified solar irradiation and the development status of a country as determining factors for the implementation potential. Naturally, a high solar irradiation is favorable and developed countries are more likely to have projects with solar process heat. Moreover, the required temperature range is a decisive factor, where lower temperatures are beneficial. This mostly refers to unit operations, whereas the integration is not specifically related to an industrial sector itself, yet it seems that food processing is a really developed sector. Almost all projects come with reduced costs compared to the conventional fuel price, which underlines the economic feasibility of solar process heat, where especially bigger projects reduce costs significantly. The identified barriers to solar integration are the availability of solar irradiation, high-temperature demand, and costs. Moreover, knowledge gaps, investment risks, lack of policy support and integration difficulty are obstacles.

Based on the designed framework for the selection of technologies 6 process technologies were identified: extended heat exchange surfaces, pervaporation, membrane distillation, oscillatory baffled reactors, pulse combustion drying and microchannel reactors. Moreover, 2 supply technologies, namely solar particles as a heat transfer medium and solar furnaces were determined. Due to the early development stage of emerging technologies, technical issues of the technologies are the main obstacles. For technologies, which have been further developed costs need to be considered and market barriers regarded. For supply technologies, the availability of solar irradiation is a premise and costs are an issue. The benefits of emerging technologies on solar integration mostly refer to a reduction in temperature demand as well as a continuous production. In case of supply technology, a higher temperature range and new storage possibilities, such as solar fuels, are advantageous. The results of the potential analysis emphasize the benefits of pulse combustion drying, microchannel reactors, and pervaporation, which have all been ranked well for each weighting scenario. All process technologies are ranked quite well in regard to their respective features. The potential of supply technologies is estimated to be a bit lower due to the lack of high solar irradiation in Northern Europe and the consequential location dependency to Southern Europe. Moreover, these technologies are associated with high costs. The scores of the potential analysis emphasize that the selected technologies are not only suitable for solar integration but also come with features which make them superior to the conventional technology. These features could be a key element in promoting a switch towards an emerging technology and moreover solar integration, as for example in the case of process technologies a reduction of costs in the supply system due to a lower required temperature could make solar integration economically feasible.

In general, it can be said that on the one hand, technologies are needed in order to allow lower process temperatures, which is promising for solar integration, since this simplifies the design of the supply side, as the technology is already advanced. On the other hand, several processes are in need of high-temperature supply. For this reason advancements on the supply side technologies for high-temperature supply are necessary. Moreover, a combination of process/process or process/supply technologies is feasible. This study emphasizes the fact that there are several technologies, both on the supply and on the process-side, which are beneficial for overcoming current technical barriers. These technologies are not only suitable for facilitating solar process heat but are generally seen as auspicious technologies. Therefore, emerging technologies play a promising role in extending the potential of solar process heat in the EU.

The results of this study emphasize the range of possibilities coming from emerging technologies. This could be seen as an impulse for companies to rethink their current process design, as a change to emerging technologies would not only favor solar integration but most likely also come with efficiency gains and a reduction in costs. The technologies are all developed to a different degree; therefore it is advisable to first focus on solar integration support schemes for technologies and application areas which are quite advanced such as microchannel reactors and extended heat exchange surfaces, as in others cases the technology has to first be further developed before solar integration can play a role.

Based on the obtained information from this study 4 steps have been identified in order to facilitate the implementation of emerging technologies in combination with solar heat in industrial processes.

Step 1: First of all, further research needs to be carried out regarding current technical issues of the emerging technologies.

Step 2: Secondly, demonstration plants are of importance to validate the feasibility and benefits of the technology and of the technology in combination with solar integration in a relevant environment. This would build up confidence in the technology of potential investors.

Step 3: Moreover, support schemes need to be designed addressing non-technical barriers to solar integration, such as knowledge gaps or high investment risks. Information needs to be spread in order to emphasize the benefits of emerging technologies. Here, it would be wise to lay a focus on the benefits in general, such as for example a higher efficiency and potentially reduced costs, and not solely on the advantages for solar integration as the first point is likely to be more motivating for companies to invest in a certain technology. Moreover, incentives and financial support schemes would reduce the currently perceived high risk of investing in novel technologies.

Step 4: Lastly, the implementation of emerging technologies in combination with solar integration needs to be advocated. This is of importance as later integration might be challenging due to the already implemented process design.

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Appendix A

Appendix A gives an overview of different unit operations, their respective industry, and the utilized equipment. This gives an indication of the correlation between unit operations and the respective industry and the employed technology.

Process	Application	Equipment	Industry
Agglomeration—Sintering	Metals Production	Various Furnace Types, Kilns, Microwave	Primary Metals
Calcining	Lime Calcining	Various Furnace Types	Cement, Wallboard, Pulp and Paper Manufacturing, Primary Metals
Curing and Forming	Coating, Polymer Production, Enameling	Various Furnace Types, Ovens, Kilns, Lehrs, Infrared, UV, Electron Beam, Induction	Ceramics, Stone, Glass, Primary Metals, Chemicals, Plastics and Rubber
Drying	Water and Organic Compound Removal	Fuel-Based Dryers, Infrared, Resistance, Microwave, Radio-Frequency	Stone, Clay, Petroleum Refining, Agricultural and Food, Pulp and Paper, Textile
Forming	Extrusion, Molding	Various Ovens and Furnaces	Rubber, Plastics, Glass
Fluid Heating	Food Preparation, Chemical Production, Reforming, Distillation, Cracking, Hydrotreating, Visbreaking	Various Furnace Types, Reactors, Resistance Heaters. Microwave, Infrared, Fuel-based Fluid Heaters, Immersion Heaters	Agricultural and Food, Chemical Manufacturing, Petroleum Refining
Heating and Melting—High-Temperature	Casting, Steelmaking, Glass Production	Fuel-Based Furnaces, Kilns, Reactors, Direct Arc, Induction, Plasma, Resistance	Primary Metals, Glass
Heating and Melting—Low-Temperature	Softening, Liquefying, Warming	Ovens, Infrared, Microwave, Resistance	Plastics, Rubber, Food, Chemicals
Heat Treating	Hardening, Annealing, Tempering	Various Fuel-Based Furnace Types, Ovens, Kilns, Lehrs, Laser, Resistance, Induction, Electron Beam	Primary Metals, Fabricated Metal Products, Glass, Ceramics
Incineration/Thermal Oxidation	Waste Handling/Disposal	Incinerators, Thermal Oxidizers, Resistance, Plasma	Fabricated Metals, Food, Plastics and Rubber, Chemicals
Metals Reheating	Forging, Rolling, Extruding, Annealing, Galvanizing, Coating, Joining	Various Furnace Types, Ovens, Kilns, Heaters, Reactors, Induction, Infrared	Primary Metals, Fabricated Metal Products
Separating	Air Separation, Refining, Chemical Cracking	Distillation, Membranes, Filter Presses	Chemicals
Smelting	Steelmaking and Other Metals (e.g., Silver)	Various Furnace Types	Primary Metals
Other Heating Processes	Food Production (including Baking, Roasting, and Frying), Sterilization, Chemical Production	Various Furnace Types, Ovens, Reactors, and Resistance Heaters. Microwave, Steam, Induction, Infrared	Agricultural and Food, Glass, Ceramics, Plastics and Rubber, Chemicals

Figure 24 Overview of industrial processes with heat demand (Lawrence Berkeley National Laboratory, 2008)

Appendix B

Questionnaire: Emerging technologies and industrial solar heat integration

This questionnaire is conducted within task 5.2 of the INSHIP project. The final deliverable 5.2.2 will be a roadmap of emerging technology on enhancing solar integration in industrial processes. For this reason, I kindly ask you to complete this questionnaire by the **4th of April**. The questionnaire is divided into 5 sections, whereas the first four specifically address the emerging technology and the last two are directed at the ranking and the weighting of the criteria for the potential calculation. If information is based on an external source, please state the source.

a.) General information

Please explain shortly the working principle of XX technology.

Please state the conventional/currently used technologies, which the emerging technology could replace.

b.) Development status:

- Which are commercial applications, demonstration projects and potential applications where the technology is employed? Please give examples and refer to the respective application areas and unit operations (e.g. cleaning, drying, evaporation, pasteurization, sterilization, heating/cooling of production halls…).
- Please state the technology readiness level of the emerging technology (see Appendix A)
- Which are current development issues of the technology?
- Which actions should be taken in order to overcome those barriers?

c.) Further Information

Please state important patents/literature sources in regard to the technology.

d.) Solar integration:

Please state the benefits the emerging technology bears on enhancing the integration of solar heat in industrial processes. Examples include a switch from batch to continuous production or lower process temperature requirements.

e.) Ranking of technology

Part of this roadmap is a potential assessment of the different emerging technologies on their ability to facilitate solar integration in industrial processes. The potential is evaluated according to the following six criteria:

- Efficiency
- Development status
- Easiness of integration of the emerging technology
- Easiness of integrating solar heat in the technology
- Costs
- Multiplicativity

Please rate the following criteria respective to the emerging technology. Within the criteria points from 1 to 5 are assigned, respectively to the properties of the technology. A more detailed description of the criteria and point distribution is given in Appendix B. The criteria Multiplicativity will be assigned separately. Developments Status can be attributed with 1, 2, 3, 4 or 5 points, while for the other criteria 1, 3 or 5 points can be assigned.

Table 27 Rating of the emerging technology

Criteria	Points
Multiplicativity	Not to be assigned
Development status	
Easiness to integrate the emerging technology	
Easiness to integrating solar heat in the technology	
Efficiency	
Costs	

f.) Weighting of criteria

In order to define the influence of each criterion on the potential of emerging technologies on facilitating industrial solar heat supply I kindly ask you to assign points to each criterion. The higher the points the higher is the influence of the certain criteria on the potential of emerging technologies in promoting solar-driven industrial heat supply, whereas 100 points are the total maximum of all criteria combined. Please keep in mind that these criteria do **not** specifically address this technology, but will be used for an overall assessment of each technology.

Table 28 Weighting of criteria

Criteria	Points
Multiplicativity	
Development status	
Easiness of integration of the emerging technology	
Easiness of integrating solar heat in the technology	
Efficiency	
Costs	
Total Points	100

Appendix C

Appendix C presents the assessment of the emerging technologies, based on their suitability to enhance solar integration in industrial processes.

Table 29 Features of non-reactive and reactive structured devices

Technology	Features	High heat transfer	High mass transfer	Active/passive enhancement method	Key feature	Lower T° than conventional		Smoother process characteristics than the conventional technology	Decision YES ≥2X
						High heat transfer coefficient	Change in the process ->Lower T°		
Advanced HX, more precisely ones with an extended heat exchange surface	High heat transfer coefficient and compact unit size	X	X	Passive	High m^2/m^3 high turbulence	XX			**Yes**
Static mixers/reactors	Continuous processing Very high energy dissipation rate->compact energy efficient units	X	X	Passive	Combination of pumping and mixing	X			**No**
Catalytic foam reactors	high area for depositing catalysts, low-pressure drop	(X) in case of metallic foams	X	Passive	High geometric area				**No**
Monolithic reactors	Decoupling of overall diameter and diameter for mass transfer, Away from turbulence to laminar flow needing less energy, Low-pressure drop, High selectivity	Poor radial heat transfer and thus poor heat removal	X	Passive	Decoupling of net flow and residence time				**No**
Millisecond Gauze reactors	high reaction rates from exothermic reactions- allowing small reactors high conversion rates			Passive	Very short residence time				**No**
Microchannel reactors	High-pressure drop, clogging tendency, very high heat transfer coefficient	X	X	Passive	Compact sizing Laminar flow regime	XXX	X	X	**Yes**
Membrane reactors	Controlled dosing of one reactant Smooth process characteristics, High mass transfer		X	Passive	Combination of chemical and membrane separation process Selective product removal			X	**No**
Membrane separation	Lower temperature demand			Passive	Selective product		XX		**Yes**

(Membrane Distillation, Pervaporation)	Higher flexibility				removal				

Table 30 Features of hybrid reactive systems and hybrid non-reactive technologies

Technology	**Principle/Features**	**High heat transfer**	**High mass transfer**	**Active/passive enhancement method**	**Key feature**	**Lower T° than conventional**		**Smoother (even) process characteristics than conventional technology**	**Decision Yes ≥2X**
						High heat transfer coefficient	Lower T° demand than conv. Tech.		
Hybrid distillation (Adsorptive distillation Extractive distillation)	Energy savings Separation of azeotropic components			Passive	Increases separation ability				**No**
Heat-integrated distillation	Energy savings	X		Passive	Heat integration between rectifying and stripping column				**No**
Chromatographic separation and reactions (SMB. Rotating annular chromatographic reactor)	Change from batch to continuous			Active	Combination of chromatographic separation and chemical reaction ->equilibrium shift			X	**No**
Gas-solid trickle flow	Low pressure drop	X	X	Active	Gas flows co/counter to the stream of fine solid particles through the second solid phase leading to high conversion rates	X			**No**
Liquid gas and liquid-liquid separation and reaction (Reactive absorption, Reactive extraction)	Absorption of gases in liquid solutions with simultaneously chemical reactions			Active	Combination of reaction and liquid/liquid/liquid/gas separation				**No**
Reactive distillation	Continuous removal of reaction products Reaction and distillation are carried out together-> higher conversion or total can be reached			Active	Higher conversion rates due to equilibrium shift				**No**

Table 31 Features of rotating energy transfer technologies

Technology	Features	High heat transfer	High mass transfer	Active/passive enhancement method	Key feature	Lower T° than conventional		Smoother (even) process characteristics than conventional technology	Decision YES ≥2X
						High heat transfer coefficient	Lower T° demand than conv. Tech.		
Centrifugal Liquid-Liquid Contractors	Short residence time, high centrifugal force, Mixing and separation in a single, compact unit		X	Active	Separation and mixing in the same reactor			X	**No**
Rotating packed beds	Increased heat/mass transfer	X	X	Active	High gravity environment leading to a really high mass transfer	X			**No**
Spinning disc reactor	High heat fluxes or viscous liquids are involved, the objective is to generate a highly sheared liquid film	X		Active	Formation on a film flow leading to very good mass and heat transfer	X			**No**

Table 32 Features of electromagnetic energy transfer technologies

Technology	Features	High heat transfer	High mass transfer	Active/passive enhancement method	Key feature	Lower T° than conventional		Smoother (even) process characteristics than conventional technology	Decision YES ≥2X
						High heat transfer coefficient	Lower T° demand than conv. Tech.		
Hydrodynamic cavitation reactor	c Increased yield and selectivity			Active	The energy of liquid flow is used to create cavitation				**No**
Impinging streams reactor	High shear and turbulence-excellent conditions for mixing and heat/mass transfer	X	X	Active	Very high mass transfer	X			**No**
Ultrasound (sonochemical, ultrasound crystallization)	High temperatures and pressures lead to fast reactions, higher heat transfer	X	X	Active	High temperatures and pressures due to the formation of cavitation	X			**No**
Supersonic gas-liquid reactor	Very high mass fluxes within a limited volume		X	Active	Using the energy of supersonic shockwaves				**No**
Electric field-enhanced extraction	Putting an electric charge on droplets can improve the required adhesion between product and the target		X	Active	Extraction rate enhancement				**No**
Induction and Ohmic heating	Electro-magnetic fields are generated by electric coils in the vicinity of this material			Active	Heat generated through eddy currents Resistive heating				**No**
Microwave enhanced operation	Energy savings, acceleration of reactions			Active	Heated directly and evenly or selective heating				**No**

Photochemical reactors	very high conversion/yield, concentrating technologies are needed in the case of solar for high fluxes, temperature does not really play a role			Active	Usage of light to initiate or catalyze reactions				**No**
Plasma(GlideArc) reactors	Plasma generation by the formation of gliding discharge			Active	Cold and catalytic plasma instead of high energy thermal processes		X		**No**

Table 33 Features of dynamic and supercritical technologies

Technology	**Features**	**High heat transfer**	**High mass transfer**	**Active/passive enhancement method**	**Key feature**	**Lower T° than conventional**		**Smoother (even) process characteristics than conventional technology**	**Decision YES ≥2X**
						High heat transfer coefficient	Lower T° demand than conv. Tech.		
Oscillatory baffled reactor	Continuous process Good mixing at long residence times Good heat transfer	X	X	Active	Tubular reactor with oscillating flow for slow intrinsic processes	XX		XX	**Yes**
Pulse combustion drying	Intensified heat transfer Can deal with a variety of materials, better quality products/efficiency	X	X	Active	Intermittent combustion->intensive pressure, velocity, and temperature waves	XX			**Yes**
Supercritical Separation	Fast reactions, temperature pressure driven			Active	Higher selectivity and speed				**No**

Appendix D

Appendix D introduces certain unit operations estimated to be suitable for solar integration.

Table 34 Temperature range of industrial processes requiring low temperature (Kalogirou, 2003)

Industry	Process	Temperature range in C°
Dairy	Pressurization	60-80
	Sterilization	100-120
	Drying	120-180
	Concentrates	60-80
	Boiler feed water	60-90
Tinned Food	Sterilization	110-120
	Pasteurization	60-80
	Cooking	60-90
	Bleaching	60-90
Textile	Bleaching, Drying	60-90
	Drying, Degreasing	100-130
	Dyeing	70-90
	Fixing	160-180
	Pressing	80-100
Paper	Cooking Drying	60-80
	Boiler feed water	60-90
	Bleaching	130-150
Chemical	Soaps	200-260
	Synthetic rubber	150-200
	Processing heat	120-180
	Pre-heating water	60-90
Meat	Washing, sterilization	60-90
	Cooking	90-100
Beverages	Washing, sterilization	60-80
	Pasteurization	60-70
Flours by-products	Sterilization	60-80
Timber by-products	Thermodiffusion beams	80-100
	Drying	60-100
	Pre-heating water	60-90
	Preparation Pulp	120-170
Bricks and Blocks	Curing	60-140
Plastics	Preparation	120-140
	Distillation	140-150
	Separation	200-220
	Extension	140-160
	Drying	180-200
	Blending	120-140

Appendix E

Appendix E gives detailed information on the ranking and reasoning of criteria.

Table 35 Potential analysis

Technology	Multiplicativity	Development status	Easiness to integrate technology	Solar integration in technology	Quality of product/reached temperature	Efficiency	Installment costs
Extended heat exchange surface	3-many but maybe small	5 - commercial	3 – mentioned as a barrier	3[3] proven example	3	5[2] higher heat transfer	2[1] more expensive
Pervaporation	2 – low flux	4 – some commercial others aren't	3	3 especially desalination	5[4] very good for high salt stuff	5[4] better selectivity	4[4]
Membrane Distillation	2	3 – not commercial application so far[10]	4 – depends if process heat network is already in place, the rating would be 5[10]	3[10]	5 – theoretical 100% rejection rate, better selectivity [11]	5 [10]	2[10]
Oscillatory Baffled Reactor	2 – niche applications	3 – only one company working, but good potential for scale-up	3	2 no examples	5 better mixing in slow reactions	5[2] better mixing	4[5]
Pulse combustion drying	4	5[21]	3[14]	4[14]-not yet proven but concept exists as it is thermal drying	5[15] –due to the elimination of property distribution (temperature)	5[16]	4-lower than installment costs of conventional combustors due to more compact sizing[4]
Microchannel reactors	2-many potential application but small throughput	5 – commercial[19]	3 –micro plant design still an issue[20]	5- really high heat coefficient, allows switch from batch to conti[18]	3	5[17] higher heat and mass transfer -> higher yield energy savings	5[20] – lower costs as less material is needed
Solar furnaces	2-few but with a huge impact,	3 – applications need further	2 – solar availability and lots	-	5[8] – higher temperature	3[9]	1[7,9] more expensive

	restricted to southern Europe	development not so much furnace design	of effort				
Solar particle technology	2- few but with a huge impact, restricted to southern Europe	2[12]	3.5[13]	-	5 – higher temperature	4[13]	2[13]

[1](Pointner et al., 2015), [2](Bergman et al., 2011), [3](Muster-Slawitsch et al., 2016), [4](Q. Wang et al., 2016), [5](NiTech Solutions Ltd, 2017b), [6](Reay et al., 2013), [7](Meier et al., 2006), [8](Roldán Serrano, 2017), [9](p.c with Flammant, G., 05.04.2018), [10](p.c. Koschikowski, J., 10.04.2018 and p.c. Zaragoza, G., 06.04.2018), [11](Drioli et al., 2015; P. Wang & Chung, 2015), [12](p.c. Johnson, E. ,13.04.2018), [13](p.c. Johnson, E. ,13.04.2018; p.c. Flammant, G., 05.04.2018), [14](Brunner et al., 2011), [15](Kudra, 2008), [16](Zbicinski, 2002), [17](Kołtuniewicz, 2014), [18](Drost et al., 2012),[19](Kołtuniewicz, 2014) , [20](Hessel, 2008),[21](Meng et al., 2016)s