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Solar Reactor

Exploratory project on process-oriented concept development of
solar reactors and their potential applications

(Sondierung prozessorientierter Konzeptentwicklung
solarer Reaktoren und deren Einsatzpotentiale)

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Abstract

The European Union (EU) defined ambitious climate goals to transform the fossil-fuel based energy system towards a low-carbon system. In October 2014, a target of 27% of renewables of the gross final energy consumption until 2030 was stipulated as part of the 2030 climate and energy policy framework. The **industry sector** as the third biggest energy consumer relies increasingly on renewable energy sources to achieve this goal. Current research and development activities focus on **innovative approaches and energy efficiency measures** for industrial processes, which allow the transformation from batch to continuous (thermal) processes and deploy new approaches for thermochemical, photocatalytic and electrolytic processes. At the same time, new reactor technologies are developed based on process intensification concepts. Process intensification is characterized by significantly lower energy (and/or exergy) requirements and increased potential for solar energy supply.

A new paradigm for industrial production and energy supply systems are **solar reactors**. A solar reactor, lacking a commonly accepted definition, can be defined as an **integrated production and supply system** where the reactors/containers and the components of the solar energy supply are amalgamated into one component. Thus, the **thermal or chemical process takes place at the same location where the incident solar radiation is absorbed**. Advantages of separating the solar supply and industrial process can lie in higher degrees of freedom regarding design, operation, control, process stability, etc. or originate from product quality requirements. On the other hand, a separation needs more components and continuous adjustment between supply and demand and can imply higher conversion, distribution and storage losses. For a broad range of applications, the advantages outweigh the disadvantages significantly. Solar reactors can lead to **higher system efficiencies, system simplifications, improved process management, better controllability and easier system integration**, resulting in **significant cost reductions**. Until now, a comprehensive qualitative and quantitative assessment of the technological and economic potential of solar reactors was missing.

This report fills this gap. It contains a semi-quantitative analysis to **identify industrial processes and reactors suitable for solar energy use with solar reactors**. Processes were classified by a traffic light labeling system, where each color indicates the suitability of a process for the solar energy supply. In the semi-quantitative analysis, **30 industrial processes from 7 different industries were investigated based on extensive data collection**. The analysis showed that more **than half of the analyzed processes have a high suitability for solar energy use with solar reactors**, namely (1) absorption/desorption, (2) adsorption, (3) blanching, (4) cooking, (5) crystallization, (6) evaporation, (7) extraction, (8) nitration, (9) pasteurization, (10) photocatalytic oxidation, (11) electrolysis, and (12) fermentation. Ten percent of the processes have a medium potential for a solar energy use whereas a quarter of the investigated processes are not suitable for a solar energy use with solar reactors.

Overall, the analysis suggests that solar reactors have a high implementation potential throughout the industry. An analysis of potential applications in energy-intensive industries opened up new perspectives for relevant stakeholders. The solar industry, technology suppliers and the producing industry can now gain a better understanding of the benefits of solar reactors and favorable deployment conditions to embrace promising investment opportunities and support the development of innovative solar reactor concept.

Kurzfassung

Die Europäische Union (EU) hat ehrgeizige Klimaziele definiert, um das auf fossilen Brennstoffen basierende Energiesystem in ein CO₂-armes System umzuwandeln. Im Oktober 2014 wurde im Rahmen der Klima- und Energiepolitik 2030 ein Ziel von 27% an erneuerbaren Energien am Bruttoendenergieverbrauch bis 2030 festgelegt. Um dieses Ziel zu erreichen, setzt die **Industrie** als drittgrößter Energieverbraucher zunehmend erneuerbare Energien ein. Aktuelle Forschungs- und Entwicklungsaktivitäten konzentrieren sich auf **innovative Ansätze und Energieeffizienzmaßnahmen für industrielle Prozesse**, welche die Umstellung von diskontinuierlichen auf kontinuierliche (thermische) Prozesse und neue Arten der thermochemischen, photokatalytischen und elektrolytischen Prozessen ermöglichen sollen. Gleichzeitig werden neue Reaktortechnologien entwickelt, die auf Prozessintensivierungskonzepten basieren. Die Prozessintensivierung zeichnet sich durch einen deutlich geringeren Energiebedarf (und/oder Exergiebedarf) und ein erhöhtes Potenzial für eine Solarenergieversorgung aus.

Ein neues Paradigma für industrielle Produktions- und Energieversorgungssysteme sind **Solarreaktoren**. Solarreaktoren, für die es noch keine allgemein anerkannte Definition gibt, können als **integrierte Produktions- und Versorgungssysteme** definiert werden, bei dem die Reaktoren/Behälter und die Komponenten für die Solarenergieversorgung zu einer Komponente verschmolzen werden. **Der thermische oder chemische Prozess findet also am selben Ort statt, an dem die einfallende Sonnenstrahlung absorbiert wird.** Die Vorteile einer Trennung von Solarenergieversorgung und Industrieprozess können in höheren Freiheitsgraden in Bezug auf Design, Betrieb, Steuerung, Prozessstabilität usw. liegen oder sich aus Anforderungen an die Produktqualität ergeben. Andererseits erfordert eine Trennung mehr Komponenten und eine kontinuierliche Anpassung zwischen Versorgung und Prozess und kann höhere Umwandlungs-, Verteilungs- und Speicherverluste zur Folge haben. Für ein breites Anwendungsspektrum überwiegen die Vorteile deutlich. Solarreaktoren können zu einer **höheren Systemeffizienz, Systemvereinfachungen, verbessertem Prozessmanagement, besserer Regelung und einer einfacheren Systemintegration** führen, was wiederum **Kosteneinsparungen** mit sich bringt. Bisher fehlte jedoch eine umfassende qualitative und quantitative Bewertung des **technologischen und wirtschaftlichen Potenzials von Solarreaktoren**.

Dieser Bericht schließt diese Lücke. Er enthält eine semi-quantitative Analyse, um zu prüfen, inwiefern **industrielle Prozesse und Reaktoren für eine solare Energieversorgung im Sinne des Solarreaktorkonzepts** geeignet sind. Die Prozesse wurden durch ein Ampelkennzeichnungssystem klassifiziert, wobei jede Farbe die Eignung des Prozesses für die Solarenergieversorgung anzeigt. Mittels der semi-quantitativen Analyse wurden 30 industrielle Prozesse aus 7 verschiedenen Branchen auf Basis einer umfangreichen Datenerhebung untersucht. Die Analyse ergab, dass mehr als die Hälfte der untersuchten Prozesse eine hohe Eignung für die Solarenergieversorgung aufweisen, nämlich (1) Absorption/Desorption, (2) Adsorption, (3) Blanchieren, (4) Kochen, (5) Kristallisation, (6) Verdampfung, (7) Extraktion, (8) Nitrierung, (9) Pasteurisation, (10) Photokatalytische Oxidation, (11) Elektrolyse und (12) Fermentation. Zehn Prozent der Prozesse haben ein mittleres Potenzial für die Solarenergieversorgung, ein Viertel der untersuchten Prozesse ist für die Integration in Solarreaktoren nicht geeignet

Insgesamt zeigt die Analyse, dass **Solarreaktoren ein hohes Umsetzungspotential in vielen Industriesektoren** haben. Eine Analyse möglicher Anwendungen in energieintensiven Branchen eröffnet relevanten Stakeholdern neue Perspektiven. Die Solarindustrie, Technologieanbieter und die produzierende Industrie können so die Vorteile von Solarreaktoren und die günstigen Einsatzbedingungen besser verstehen, um vielversprechende Investitionsmöglichkeiten zu nutzen und die Entwicklung eines innovativen Solarreaktorkonzeptes zu unterstützen.

1 Introduction

1.1 Transformation of industrial production with solar reactors

The European Union (EU) defined ambitious climate goals to transform the fossil-fuel based energy system towards a low-carbon system. In October 2014, a target of 27% of renewables of the gross final energy consumption until 2030 was stipulated as part of the 2030 climate and energy policy framework [1]. The industry sector as the third biggest energy consumer relies increasingly on renewable energy sources to achieve this goal [2].

Current research and development activities focus on innovative approaches and energy efficiency measures for industrial processes, which allow the transformation from batch to continuous (thermal) processes and deploy new approaches for thermochemical, photocatalytic and electrolytic processes (e.g. [3], [4], [5]). At the same time, new reactor technologies are developed based on process intensification concepts. Process intensification is characterized by significantly lower energy (and/or exergy) requirements and increased potential for solar energy supply.

A new paradigm for industrial production and energy supply systems are solar reactors. A solar reactor, lacking a commonly accepted definition, can be defined as an integrated production and supply system where the reactors/containers and the components of the solar energy supply are amalgamated into one component. Thus, the thermal or chemical process takes place at the same location where the incident solar radiation is absorbed. This differs from conventional solar energy technologies (solar thermal collectors, photovoltaic (PV) cells, etc.), which are characterized by a separation of the solar energy production and its industrial use. For solar thermal systems, external or internal heat exchangers are used to separate production and demand side. Solar PV systems typically use inverters to transform direct current (DC) to alternating current (AC). After the distribution, an AC/DC inverter might be needed if the process uses DC, e.g. for electrolytic units. Advantages of separating the solar supply and industrial process can lie in higher degrees of freedom regarding design, operation, energy supply control, process stability, etc. or originate from product quality requirements. On the other hand, a separation needs more components and continuous adjustment between supply and demand and can imply higher conversion, distribution and storage losses. For a broad range of applications, the advantages outweigh the disadvantages significantly. Solar reactors can, lead to higher system efficiencies, system simplifications, improved process management, better controllability of the process and product quality and easier system integration, resulting in significant cost reductions.

At the beginning of the project, a comprehensive qualitative and quantitative assessment of the technological and economic potential of solar reactors was missing. An analysis of potential applications in energy-intensive industries can open up new perspectives for relevant stakeholders. The solar industry, technology suppliers and the producing industry need to gain a better understanding of the benefits of solar reactors and favorable deployment conditions to embrace promising investment opportunities and support the development of innovative solar reactor concept.

1.2 Objectives, methodology and outline

The exploratory project *Solar Reactor* (Solarreaktor) addresses these opens questions by a systematic assessment of the technological and economic potential of solar reactors in the industries, using the following approaches:

- Screening of existing solar reactor concepts and use of solar energy in the industries
- Screening of industrial reactors and process intensification approaches
- Identification of key industrial processes (thermal, thermochemical, photocatalytic, electrolytic) of the most energy-intensive manufacturing sectors in the EU industry
- Assessment of the suitability for solar energy supply and solar reactor technologies/concepts for these processes based on a semi-quantitative analysis (evaluation matrix) with reference to existing industrial reactors and process intensification approaches, existing solar reactors and new solar reactor concepts

Within the project, four basic concepts for radically innovative solar reactors were developed. These will be further elaborated in follow-up research projects and are not part of this report. The major input of this report was given by the master thesis of Raphaela H. Maier [6], who worked a master student at AEE INTEC about solar reactors.

The structure of the reports is as follows. Chapter 2 gives a general overview about the solar energy use in the industries, different modes of solar energy utilization, industrial reactors and process intensification approaches. Chapter 3 introduces existing solar reactors. Chapter 4 contains the potential analysis for solar reactors. The results of the analysis, which is the main outcome of this report, are summarized in Chapter 5. Chapter 6 discusses opportunities and challenges for the further development of solar reactor concepts and Chapter 7 provides the summary.

2 Solar energy in the industries

2.1 Use of (solar) energy

In 2016, the final energy consumption in the EU reached 46,382 PJ [2]. The biggest consumers are the transport sector with a share of 33%, the residential sector (26%) and the industry (25%) [2]. The EU industry sector consists of 13 different branches. Their energy consumption differs widely, as Figure 2-1 shows. The five most energy-intensive branches are the chemical and petrochemical, iron and steel, non-metallic minerals (cement), paper, pulp and print and food and tobacco industry. These industries have a yearly demand of more than 1,000 PJ respectively.

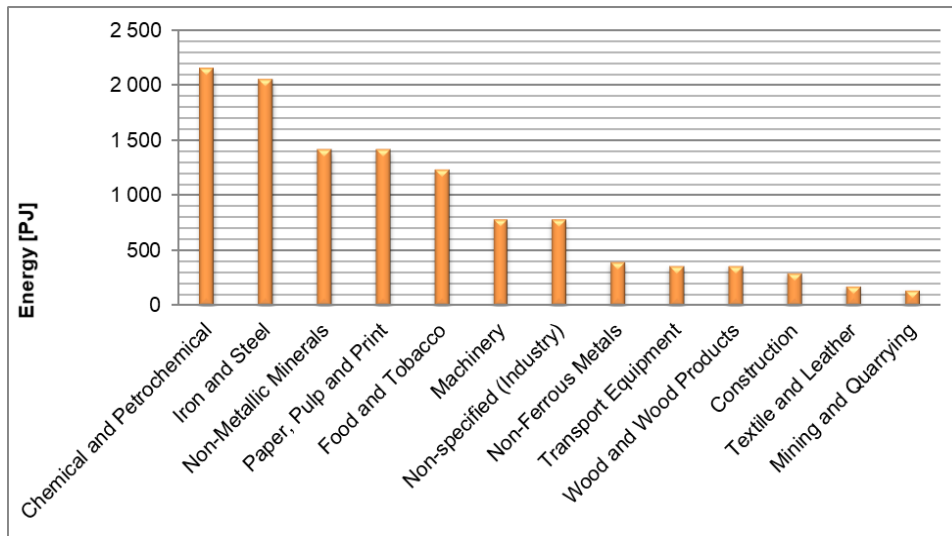


Figure 2-1: Final energy consumption by industry sector (EU-28) in 2016 [2]

Figure 2-2 shows the final energy consumption in the EU industry by fuel type. Gas is by far the most common fuel covering 59% of the energy demand. Advantages of gas are its easy conversion into mediums like hot water or steam. Furthermore, high temperatures can be achieved by gas combustion, which is crucial in many industries like in iron and steel production [7]. Solid fuels have a share of 23% of final energy consumption. With a share of 16%, renewable energies are the third most used energy source. Renewable energies include solar, wind, biomass, geothermal, hydropower and ocean resources, solid biomass, biogas and liquid biofuels [8].

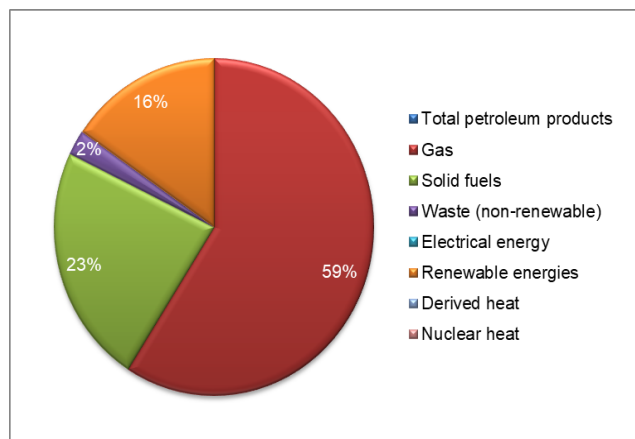


Figure 2-2: Final energy consumption in industry (EU-28) by fuel in 2016 [2]

Industrial processes for which solar energy is used can be either thermal or chemical (see Figure 2-3). Thermal processes are divided in high, medium and low temperature processes. Chemical processes are classified based on the way the chemical reaction is triggered which can be thermo-chemical, photocatalytic, electrolytic and bio-chemical. Thermo-chemical processes are further characterized by the temperature level.

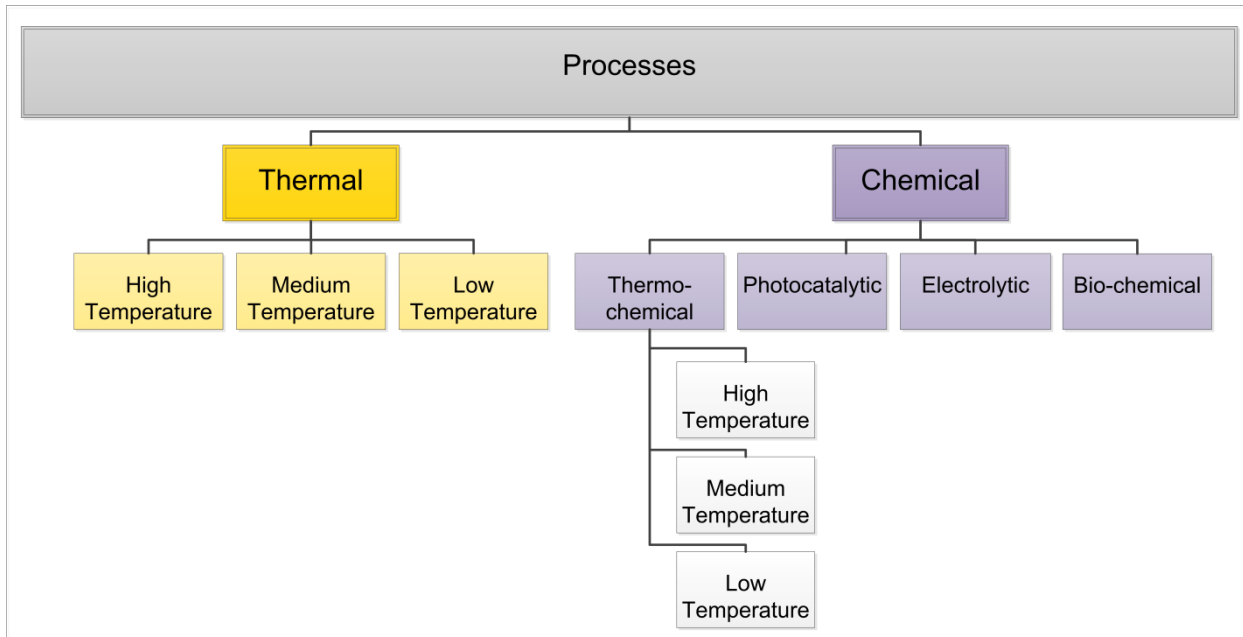


Figure 2-3: Categorization of industrial processes suitable for solar energy supply

Temperature levels are defined as follows: High temperature processes need temperatures above 400 °C, which applies for example to melting and casting in the iron and steel industry [7]. Medium temperature processes have a temperature range between 100 and 400 °C. Examples are drying or distillation in the food and chemical sectors [9]. Low temperature processes require a temperature level of less than 100°C. This includes processes as dyeing in the textiles industry or drying in the wood industry [10].

2.2 Technologies for solar energy utilization

Solar energy can be utilized in thermal, photocatalytic or electric fashion. These possibilities also apply to solar reactors. In this section, a basic description of these three possibilities are given.

2.2.1 Thermal utilization of solar energy

The thermal utilization of solar energy can be done with active or passive systems. For industrial processes, mainly active systems are used. The basic principle of active solar thermal heat utilization is the conversion of short-wave solar radiation into heat (photo-thermic conversion) by absorbing the solar radiation with a suitable collector.

Collector types can be classified according to the heat transfer medium (liquid or air) and how they absorb radiation (concentrating or non-concentrating) [10]. Concentrating systems use beam radiation with one or two-axis tracking [12]. Common collector types are non-concentrating flat plate collectors with a liquid as a heat transfer medium, using an absorber with anti-reflective cover (see Figure 2-4). They are typically used for temperature level till 100 °C or slightly above [12], [13].

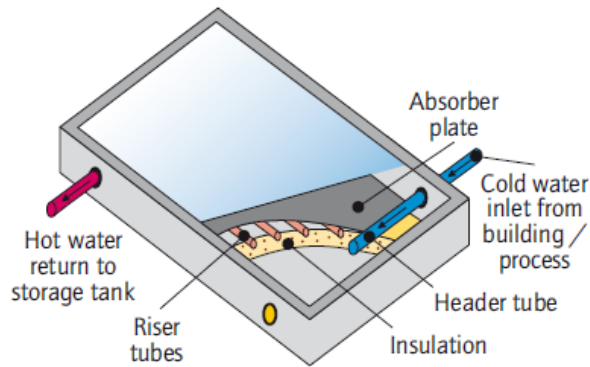


Figure 2-4: Flat Plate Collector [14]

Evacuated tube collectors achieve higher temperatures than flat plate collectors and are also common in the industry. Evacuated tube collectors consist of vertical absorber tubes (Figure 2-5). The heating transfer medium is pumped through the absorber pipes. Each tube is encapsulated by a glass tube with a vacuum to reduce the heat losses [12], [13].

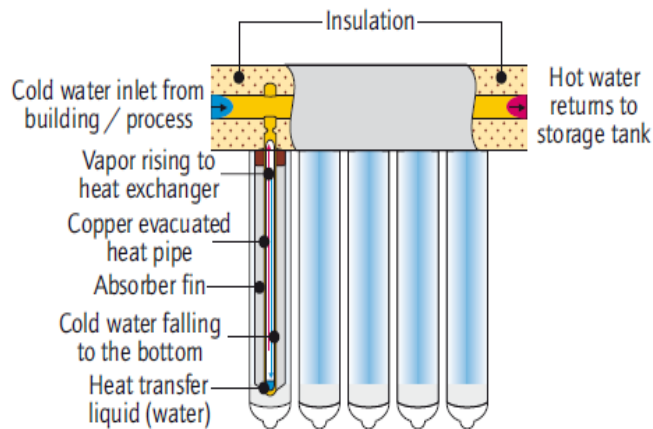


Figure 2-5: Evacuated tube collector [14]

2.2.2 Electrical utilization of solar energy

Photovoltaic (PV) cells convert solar radiation into electrical energy. PV cells use the photovoltaic effect that occurs when light strikes a p-n junction. PV cells are composed of semi-conductor layers, of which one outer layer, the so-called n-layer, is negatively charged and the other outer layer, the p-layer, is positively charged. The layer between p-layer and n-layer is called p-n-junction, where an electric field exists. When light falls on the solar cell, the released electrons move through the electric field in the p-n-junction and generate an electric voltage [10].

Typical solar cells are based on silicon and can either be n-type solar cells (see Figure 2-6) or p-type solar cells (see Figure 2-7). The former refers to a negatively charged silicon base layer and the

latter to positively charged silicon. P-type solar cells are mainly implemented in first generation PV technologies, whereas N-type solar cells are deployed in second generation PV with a specialization of thin-films [15], [16].

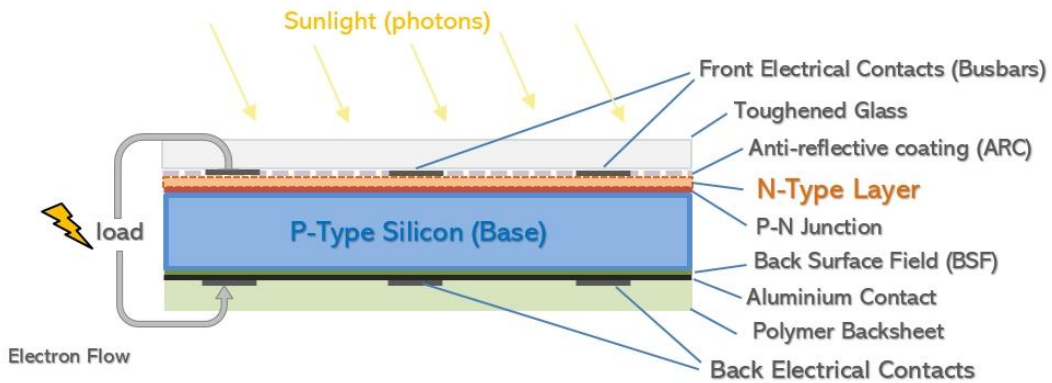


Figure 2-6: Scheme of a p-type crystalline solar cell [15]

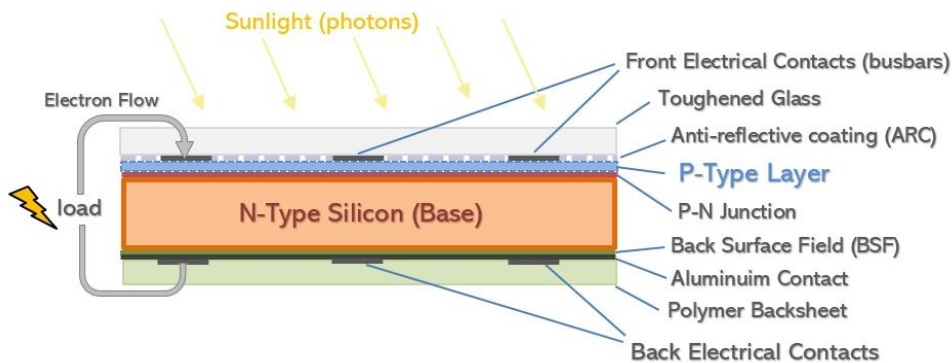


Figure 2-7: Scheme of a n-type crystalline solar cell [15]

2.2.3 Photocatalytic utilization of solar energy

In solar photocatalytic utilization, photons are absorbed directly by reactants and/or a catalyzer that triggers a reaction [17]. The energy of solar photons depends on the wavelength of the absorbed UV-rays and can be determined through Planck’s Law [17]. The UV-range of sunlight can be divided into 3 sub-categories according to wavelength: (1) UV-A with wave length $\lambda = 315-400$ nm, (2) UV-B with $\lambda = 280-315$ nm and (3) UV-C with $\lambda = 100-280$ nm [19]. Due to the Rayleigh scattering and the gas absorption in the ozone layer, UV-A is 10 to 100 times more abundant than UV-B. UV-C is almost completely absorbed in the atmosphere [20]. As a result, mainly UV-A rays of sunlight are used for photocatalytic technologies.

Photochemical processes are often carried out with photocatalysis. In photocatalysis, a photoreaction is accelerated by using a catalyzer like the semiconductor material (TiO_2) for better absorption of UV radiation. So called Advanced Oxidation Processes (AOPs) are photocatalytic processes. AOPs are chemical treatment processes which form hydroxyl radicals (OH^\cdot) which are highly reactive and degrade chemically and biologically substances. The formation of OH^\cdot among others is

achieved by the energy input from UV radiation. AOPs, for example, are applied in the treatment of waste water [21].

2.3 Industrial Reactors

A large variety of chemical and physical processes are used in industrial reactors. In order to meet the requirements of these processes with regard to reaction mechanism, phase changes, peculiarities of the respective activation principle as well as pressure and temperature conditions in the technical implementation, a large number of reactors is needed [22].

Here, a classification of reactors is carried out according to the following criteria: (1) fluid mechanics, (2) thermal engineering and (3) phase changes. The first two criteria allow a characterization of reactors according to their suitability for different applications. The third criteria, the number of phase changes occurring during a reaction, is important for the reactor type, because it highly influences the energy and mass transfer [22].

2.3.1 Reactor classification based on fluid mechanics

For reactors with **discontinuous/batch operation**, all raw products are initially fed to the reactor and during the reaction, neither educts are added or products are taken out. After the reaction is over, the entire reaction mass is removed from the reactor and a new reaction cycle is prepared. Advantages of a batch operation are: (1) high flexibility, as one reactor can be used for the production of different products, (2) high turnover due to uniform reaction times. Disadvantages are: (1) dead times due to filling, emptying, heating, cooling and cleaning of the reactor, (2) high measuring and control effort due to the transient process and (3) occurrence of quality fluctuations [22], [23].

For reactors with **continuous operation** or flow operation, the reaction materials are continuously fed to the reactor in the feed stream and reaction parameters (temperature, pressure, concentration, flow) are constant over time. Advantages of this reactor type are: (1) high mechanization and automation of the process, (2) consistent product quality, (3) short dead times. The disadvantages are: (1) low flexibility, due to the limitation to minor parameter changes and the requirement of a consistent raw material and (2) comparably high investment costs [22], [23].

Reactors with **semi-continuous operation** operate discontinuously only for some of the reactants [22], [23]. Advantages and disadvantages depend on the specific implementation.

2.3.2 Reactor classification based on thermal engineering

For industrial processes, heat is either supplied (endothermic reactions) or released (exothermic reactions) from the reactor. Therefore, a distinction is made between isothermal, adiabatic and polytropic operating modes and the corresponding thermal reactor types [22].

Isothermal reactors are characterized by a spatial and temporally uniform temperature distribution within the reactor. Isothermal conditions can be achieved by different reactor designs, e.g. by stirring devices. A temporally constant temperature can only be achieved in a continuous, but not in batch operation.

Adiabatic reactors are characterized by the fact that no cooling or heating equipment is used. Reaction heat remains completely in the reaction mixture as the reaction chamber is thermally insulated. For exothermic reactions, the temperature rises whereas for endothermic reactions, the temperature drops.

Polytropic reactors have cooling or heating devices which enable stable temperature conditions within the reaction chamber or discontinuous operation over time. Based on the mathematical model of polytropic reactors, it is possible to calculate the reaction temperature at a given inlet temperature - or vice versa the necessary temperature of the inlet mixture at a given desired reaction temperature [22].

2.3.3 Reactor classification based on phase changes

Chemical reactions take place in liquid, gaseous and solid substances and the reaction partners and products can be present in all three aggregate states. Monophasic and multiphasic reactors are commonly used [22].

Monophasic reactors can be categorized into homogenous liquid phase reactors and homogeneous gas phase reactors. The former reactor type includes basically all fluidic reactor types (stirred tank, plug flow tube reactor, etc.) whereas the homogenous gas phase reactor is always built as a flow reactor [22].

Multiphasic reactors are further classified by the reaction type: (1) fluid-solid reactions, (2) solid-solid reactions and (3) fluid-fluid reactions [22]. Reactors for fluid-solid reactions can be catalyzed or non-catalyzed. In catalyzed fluid-solid reactors, the solid functions as the catalyst. It can be distinguished between three different reactor types: (1) heterogeneous gas catalytic reactors with solid catalyst and gaseous reaction mixture (flat-bed reactor, plate reactor, spray tower, packed column), (2) heterogeneous-liquid catalytic reactor with solid catalyst and liquid reaction mixture (flat-bed reactor, plate reactor, spray tower, packed column), (3) three-phase reactor with solid catalyst and with the reactant present in both fluid phases (fluidized bed reactor). For non-catalyzed fluid-solid reactions reactants are given in fluid form and other reactants in solid form, resulting in two different reactor types: (1) reactors for non-catalytic gas-solid reactions (flat-bed reactor, plate reactor, spray tower, packed column), (2) reactors for non-catalytic liquid-solid reactions (flat-bed reactor, plate reactor, spray tower, packed column).

2.4 Process intensification

According to the European process intensification roadmap, process intensification consists of “a set of often radically innovative principles (‘paradigm shift’) in process and equipment design that bring significant (more than factor of two) benefits in terms of process and plant efficiency, capital and operating costs, quality, waste, process safety and more” [24]. The three main functions of process intensification are explained below.

2.4.1 Minimizing plant sizes and merging of unit operations

An important field of research are micro-reactors, which have sizes below 1 mm and are suitable for continuously running reactions [25]. These reactors are a key technology for the trend towards compact

modular factories in container formats due to their scalability. Furthermore, mixing and residence time control with heat exchange can be integrated to enable a better reaction performance. Thus, a single reactor enables a modular adaption to different process operations [26]. Examples of compact reactors besides micro-reactors are: (1) plate reactor, (2) continuous fluidized bed, granulation and drying system, (3) tube (bio)reactor, (4) oscillatory baffled reactor.

2.4.2 Increase of heat and mass transfer

An increase of heat and mass transfer can be achieved actively through the introduction of a new force, such as oscillation or radiation, or passively by enlarging the transfer conditions, such as extended heat exchange surfaces [27]. In general, the following approaches exist to raise the heat transfer rate [28]: (1) increase of temperature gradients, (2) increase of heat transfer area, (3) increase of heat transfer coefficient, (4) transformation to energy supply without thermal gradients.

2.4.3 Improvement of process control

Recently, a trend from batch to continuous process control can be observed. The main advantage of a continuously running process from a solar supply perspective is a constant energy demand. In batch processes, there are high peaks when the batch starts. In contrast, for a continuously running process a smaller quantity is produced without intermittence. This allows to dimension the energy supply technology to a lower capacity and makes the integration of renewable energy sources easier [28]. Additional advantages of a continuous process are [28]: (1) unchanged reaction conditions and product quality, (2) higher concentrations and smaller reaction volume, (3) precise temperature control, (4) less dead time, (5) easier automation and reduction of labor costs, (6) higher safety due to reduced storage of hazardous chemicals, (7) reduced energy peak load.

3 Existing solar reactor concepts and applications

To assess the technological and economic potential of solar reactors, it is import to look at already existing concepts. Lacking a commonly accepted definition, solar reactors can be defined as integrated production and supply systems where the reactors/containers and the components of the solar energy supply are amalgamated into one component, i.e. the thermal or chemical process takes place at the same location where the incident solar radiation is absorbed.

Solar reactors are not yet widely used in the industries, but there are some niche applications. Among these, photocatalytic drinking water treatment and solar melting of soda-lime-silica glass will be presented in detail. Additional application and prototypes include solar distillery for essential oil extraction [29], coffee roaster [30], solar drying [31], [32], pasteurization [33], CO₂ emission free cement production [34], aluminum recycling [35], solar fuels [36], [37], water desalination [38], depolymerization [39] and photobioreactors for algal cultures [40].

3.1 Photocatalytic drinking water treatment

In developing countries, oftentimes no reliable drinking water infrastructure exists. The treatment of drinking water lies in the responsibility of the consumer. Various methods for the treatment of household water are used including filtration, flocculation, chlorination and thermal and UV disinfection [41]. UV and thermal disinfection are preferred methods in developing countries due to abundantly available solar radiation in these regions. Additional chemicals or complex mechanisms are not necessary for solar disinfection (SODIS) in transparent containers. A common practice is the microbial inactivation in polyethylene terephthalate (PET) bottles. However, the treatment of water in PET bottles is limited to a volume of less than 3 l, which requires an average household to have sufficient bottles and time to prepare enough drinking water. Moreover, in cloudy weather the solar exposure of PET bottles needs a minimum of two days to ensure the required quality of drinking water [42].

To overcome these restrictions, a SODIS enhanced batch reactor (EBR) with a volume of 25 l was designed to generate safe drinking water for an average household [43]. The reactor is controlled batch-wise as earlier studies found out that bacteria inactivation is more effective when exposed to a lethal UV-A dose for a short period rather than for a longer period under sub-lethal doses when recirculating in the reactor [44]. The EBR was designed and built from a methacrylate tube placed in the linear focus of a compound parabolic concentrator (CPC) collector and mounted at 37° inclination (see Figure 3-1). The CPC concentrates sunlight with a factor of two, both direct and diffuse radiation. It is therefore not necessary to reorient the reactor to track the sun for optimized absorption. After 5 h the reactor achieves a complete bacteria inactivation in periods of strong sunlight. Under cloudy conditions and with low solar intensity, water must be treated up to 2 days in the EBR to ensure drinking water quality standards [42].



Figure 3-1: Solar disinfection reactor (SODIS) [42]

3.2 Solar melting of soda-lime-silica glass

Experimental studies on melting soda-lime-silica glass in a High Flux Solar Simulator (HFSS) were conducted by [45] at the Paul Scherrer Institute in Switzerland. The soda-lime-silica glass is used for container, flat glass and glassware and is therefore widely available. The melting temperature of the raw material is around 1,500 °C. Large-scale furnaces efficiently produce 300 to 600 tons of glass per day. There are also day tanks which produce on a smaller scale about 0.07 to 1.1 tons per day. The direct solar glass melting experiments mainly focus on smaller scale businesses. The HFSS simulates a solar beam by using 10 kW Xenon arc bulbs with ellipsoidal reflectors to generate a beam of concentrated radiation with a specific spectral distribution [45], [46].

The furnace is constructed with an inner diameter of 187 mm and a 120 mm deep fused silica crucible in which the glass melt is located. All this is surrounded by an insulated box (see Figure 3-2). At the top of the furnace, an opening of 6 cm captures the concentrated beam and directs to the surface of the melt. Additionally, an outlet tube was installed at the bottom of the furnace to drain molten glass for further forming purposes. The tubes function as a freeze-thaw valve to control the outflow of the glass [45], [46].

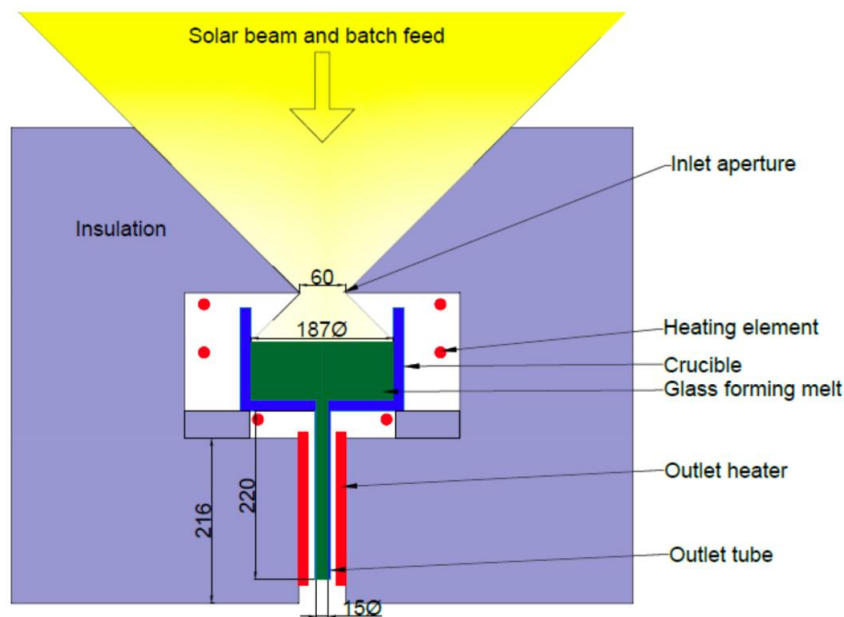


Figure 3-2: Schematic drawing of glass melting furnace with solar beam [45]

4 Potential analysis for solar reactors

The assessment of the technical and economic potential regarding solar energy supply and solar reactor technologies/concepts was done for 30 processes. For the selected processes, a semi-quantitative analysis was used, where the fulfillment of quantitative and qualitative criteria was assessed

independently. These results were then merged, which lead to the final assessment. Figure 4-1 gives an overview of the methodology.

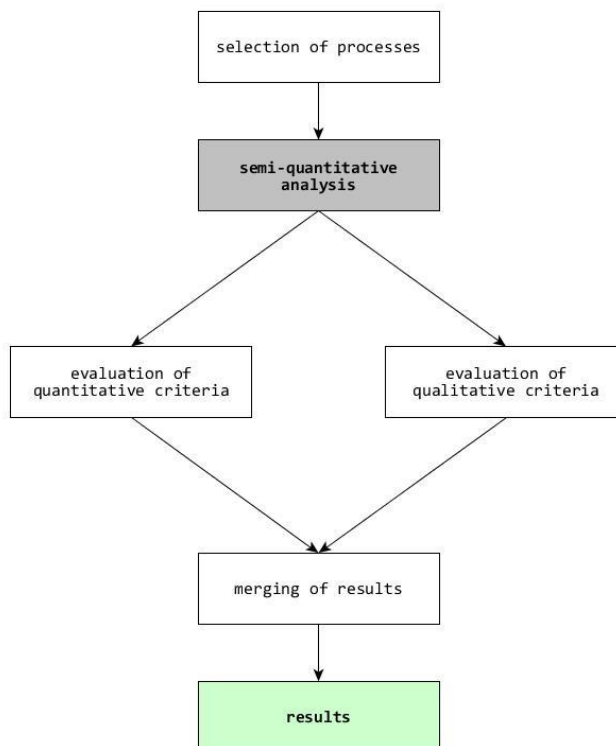


Figure 4-1: Overview of the assessment method

4.1 Selection of processes

In a preliminary step, 30 processes from 7 different industries were analyzed, amounting to a total of 44 investigated applications. The analyzed industry branches include the 5 most energy-intensive ones in the EU. These are the chemical and petrochemical industry, iron and steel industry, non-metallic minerals (i.e. cement) industry, pulp and paper industry and food industry (see section 2.1) [2]. Additionally, the non-ferrous metals (i.e. aluminum) industry and the textiles industry are included as earlier research activities show a high potential for solar energy supply in these sectors [47], [48]. The chemical and petrochemical industry was divided into sub-sectors. The analysis focused on the production of large volume organic chemicals (esters, aldehydes) and inorganic chemicals (ammonia), organic fine chemicals, chlor-alkali and polymers. Mechanical processes, which are characterized by low energy consumption, were not considered in the study. The selected processes are listed in Table 4-1. A detailed description of the processes can be found in [6].

Table 4-1: Overview of processes considered in the semi-quantitative analysis by industry sector

Explanation: yellow: thermal and thermo-chemical process; blue: photocatalytic process; purple: electrolytic process; green mark: bio-chemical process

Chemical industry	Food industry	Iron and steel industry	Non-ferrous metals industry	Non-metallic minerals industry	Paper and pulp industry	Textiles industry
Absorption/Desorption	Absorption/Desorption	Absorption/Desorption	Converting	Calcination	Absorption/Desorption	Bleaching
Adsorption	Adsorption	Melting	Smelting		Adsorption	Drying
Cracking	Blanching	Quenching	Electrolysis		Bleaching	Dyeing
Crystallization	Bleaching	Secondary metallurgy			Cooking	
Evaporation	Cooking				Drying	
Nitration	Distillation				Evaporation	
Oxidation	Drying				Oxidation	
Polymerization	Evaporation				Precipitation	
Depolymerization	Extraction				Aerobic/Anaerobic Waste-water Treatment (WWT)	
Photocatalytic oxidation	Oxidation					
Electrolysis	Pasteurization					
	Roasting					
	Sterilization					
	Fermentation					

4.2 Criteria for semi-quantitative analysis

Processes were evaluated using criteria covering technical, economic and environmental aspects. The set of criteria is intended to give an interdisciplinary assessment of the main parameters determining an industrial process. The choice of criteria must follow general rules regarding performance and quality indicators of processes [49]: (1) First, the consistency with the representation target must be ensured. In other words, the criteria must provide information which is useful to determine the suitability of solar energy utilization. (2) Second, the level of detail of the criterion is decisive. As the analysis considers many industry sectors, the acquired data of single processes were generalized and abstracted from detailed process configurations. (3) Third, the economic impact of the criterion must be considered, i.e.

the expenses for collecting data. In this case, expenses refer to the time spent to gather information for each criteria and process. (4) Lastly, the simplicity of its application is a crucial property of a criterion. The criterion should be easily understood and applicable.

Considering these rules, a set of nine criteria was determined.

Table 4-2 gives an overview of the criteria and their type (quantitative, qualitative) and scope (technical, economic, environmental).

Table 4-2: Overview of criteria of the semi-quantitative analysis

	Technical	Economic	Environmental
Quantitative Criteria	[C1] Temperature level	[C7] Market share	
Qualitative Criteria	[C2] Controllability		[C8] Product quality
	[C3] Reactor type		[C9] Energy self-sufficiency
	[C4] Space requirement		
	[C5] System complexity		
	[C6] Research development		

The differentiation between quantitative and qualitative criteria is based on the available data and the possibility to quantification, which led to the two quantitative criteria temperature level and market share. The remaining criteria are described in a qualitative manner as a quantification would lead to a loss of information. The main data source are the Best Available Techniques Reference Documents (BREF) published by the EU [50]. These include data about process properties for different industry sectors. If BREF data was insufficient, additional literature research was done. Below, the criteria are described in detail.

4.2.1 [C1] Temperature level

Studies examining the integration of solar heat into industrial processes show that *temperature levels* up to 200°C are suitable for solar energy supply [51]. These figures are derived from the efficiency of state-of-the-art collectors and solar radiation potentials in various geographic regions. It was assumed that low and medium temperature levels are easier to achieve than high temperatures. It must be emphasized, that this criterion is only applicable to the thermal energy supply of processes, whereas the investigated solar energy supply technologies also include UV-rays from sunlight.

4.2.2 [C2] Controllability

The criterion *controllability* refers to the mode a process is carried out, either continuous or discontinuous/batch-wise (see section 2.3.1). In a batch process, a finite quantity of the product is finished once at a time. When the product is ready, the reactor is emptied and cleaned before the next batch starts. In contrast, in a continuous process, smaller quantities are constantly treated in the reactor.

According to process intensification strategies (see section 2.4 **Fehler! Verweisquelle konnte nicht gefunden werden.**) the controllability is a crucial parameter for the integration of renewables. A continuous process is preferable for the integration of solar energy. It must be emphasized that the controllability also depends on the criterion *reactor type* and *product quality* because the reactor type must allow the required controllability mode and the product quality must be ensured independent on how the reactor is operated.

4.2.3 [C3] Reactor type

The criterion *reactor type* gives useful insights into the basic process dynamics and its implementation in a solar reactor. The more complex a reactor is, the more difficult it is to adjust the existing technology to a solar reactor or switch to a simpler design. Considering the basic reactor types, mono- and bi-phasic reactors are simpler in design and therefore considered more suitable for solar energy supply than tri-phasic reactors or reactors with a different reaction principle.

4.2.4 [C4] Space requirement

The criterion *space requirement* refers to the area a reactor occupies in a facility. In the past, reactors have been designed to cover the peak production capacities. This often resulted in very large and inefficient reactors. According to process intensification strategies, innovative reactors aim for modular construction designs to increase the flexibility for load changes and volatile energy supply (of solar energy). This results in a more energy efficient operation and enables a better match of energy demand and supply. Traditional chemical reactors have dimensions of 1 mm to 10 m length (horizontal) or height (vertical) [25]. In recent years so called micro-reactors became more widespread. They provide a good basis for the development of solar reactor concepts [52]. Micro-reactors have a size smaller than 1 mm [25]. The criterion *space requirement* assesses the suitability of solar energy supply better if there is the possibility to substitute existing reactor with intensified reactors or micro-reactors. Overall, it was assumed, that very large reactors achieve efficiency improvements, when the size is reduced.

4.2.5 [C5] System complexity

The criterion *system complexity* describes the number of components needed to run a process. Conventional processes are often characterized by large piping systems, valves, heat exchangers and inverters to supply the energy [51]. Furthermore, additional equipment is needed for the energy supply (e.g. power plants, generators, heat pumps, boilers etc.) and clean the flue gases (e.g. absorber, cyclones, etc.) in case of fossil-fuel based generators. Disadvantages of large piping systems are higher equipment costs and energy losses [53]. Processes characterized by high system complexity aim for simplifications. Complex systems are attributed higher suitability in terms of a solar energy supply as simplifications can be expected.

4.2.6 [C6] Research development

The criterion *research development* includes information about current research and development activities of a process with regard to solar energy supply. For this criterion, literature covering basic research (i.e. influence of UV-rays on certain chemical reactions) to successful industrial applications

(see section 3) was screened. If new concepts are discovered and their applicability has been proven, the score for this criterion is higher.

4.2.7 [C7] Market share

The criterion *market share* is defined by the turnover (in EUR) per year of an industry within the EU. For each process the turnover of the industry sector to which the process belongs to, was chosen because data was not available for each individual process. For the assessment of this criterion, it was assumed that the bigger the industry, the higher the potential for research and development activities in terms of solar energy.

4.2.8 [C8] Product quality

The criterion *product quality* consists of parameters and threshold values which determine the quality of the produced. Each process pursues a specific goal. For example, pasteurization aims to destroy bacteria. Due to the large variation of processes, parameters and threshold values required for this criterion differ widely throughout the investigated processes (i.e. moisture content in drying or removal efficiencies in absorption). Hence, this criterion is not perfectly comparable among the processes but gives relevant information about potential barriers and challenges when achieving a process target.

4.2.9 [C9] Energy self-sufficiency

Energy self-sufficiency of a process is achieved by decentralized, autonomous renewable energy supply, heat recovery systems or the use of by-products as energy fuel [54], [55]. Self-sufficiency leads to cost reduction due to lower energy costs and additional environmental benefits as emissions can be reduced. Processes with higher self-sufficiency rates are considered to have a lower potential for solar energy supply.

4.2.10 Summary of criteria

Table 4-3 provides an overview which process characteristics are preferred for each criterion.

Table 4-3: Overview of evaluation criteria. A process has higher suitability in relative terms if its characteristics belong to the column “higher suitability” compared to “lower suitability”

Criterion	higher suitability	preferred to	lower suitability
[C1] Temperature level	low temperatures	>	high temperatures
[C2] Controllability	continuous	>	discontinuous/batch
[C3] Reactor type	mono- and bi-phasic reactors	>	tri-phasic reactors, other reactor types
[C4] Space requirements	large	>	small
[C5] System complexity	high complexity	>	low complexity
[C6] Research development	advanced research	>	little/no research
[C7] Market share	high market share	>	low market share
[C8] Product quality	low requirements	>	high requirements
[C9] Energy self-sufficiency	high self-sufficiency	>	low self-sufficiency

4.3 Evaluation

The evaluation was done for all selected processes (see section 4.1). In the first step, quantitative and qualitative criteria were evaluated separately. Second, the results from the quantitative and qualitative evaluation were merged for the final assessment of a process. Whereas the quantitative and qualitative criteria could be treated as being independent from each other, there were dependencies between qualitative criteria. Summing up the scores for the quantitative criteria independently of the process under consideration would have distorted the evaluation. Therefore, an overall qualitative evaluation taking into consideration all qualitative criteria and their interplay was used.

Quantitative and qualitative evaluations were done with a traffic light labeling system by classifying processes in high, middle or low suitability for solar energy supply. The advantages of this scheme are its simplicity and universal recognition. The suitability is expressed in one of three categories (labels):

- **Green:** high
- **Orange:** middle
- **Red:** low

4.3.1 Quantitative evaluation

The two quantitative criteria are temperature level [C1] and market share [C7]. For both criteria, thresholds for high, middle and low suitability were defined. The overall score for the combination of criteria is shown in Table 4-4.

Table 4-4: Classification of quantitative criteria

	Market Share		
	>500 billion EUR/a	150-500 billion EUR/a	<150 billion EUR/a
Temperature Level			
< 100 °C	high	middle	middle
100 - 400 °C	middle	middle	low
> 400 °C	middle	low	low

4.3.2 Qualitative evaluation

All qualitative criteria were evaluated in a descriptive manner. The information gathered from each criterion were critically reviewed and dependencies between the criteria were made explicit in order to gain an overall assessment of the suitability of the process for solar energy supply. The suitability is expressed in one of three categories (labels):

- **Green:** high
- **Orange:** middle
- **Red:** low

4.3.3 Calculation of final results

The quantitative and qualitative analyses were merged. Each quantitative and qualitative category was given a score

- **Green** (high) +1
- **Orange** (middle) 0
- **Red** (low) -1

For the overall score, the score of quantitative analysis was weighted with a factor of 1, whereas the score of the qualitative analysis was weighted with a factor of 3, taking into account that the qualitative analysis covered more aspects than the quantitative analysis. The total score of the semi-quantitative analysis $score_{tot}$ is calculated as follows

$$score_{tot} = (1 * score_{quant}) + (3 * score_{qual}) \tag{Eq. 1}$$

where $score_{quant}$ represents the result of the quantitative analysis and $score_{qual}$ the result of the qualitative analysis. This score is then again converted to a traffic light labeling:

- **Green** (high) if $score_{tot} > 1$
- **Orange** (middle) if $score_{tot} \geq 0$ and ≤ 1
- **Red** (low) if $score_{tot} < 0$

4.3.4 Example: distillation process

The distillation process is characterized by a temperature level between 38°C and 270°C. Depending on the specific application, the distillation process belongs to the low (< 100 °C) or medium (100 – 400 °C) temperature range as the process can be run at different temperature levels. For the evaluation, distillation was assumed to be in the medium temperature range. The data for the distillation process regarding *market share* refers to the food industry. The turnover of the food industry is 1,039 billion EUR/a. This market share is on the upper level of the manufacturing sector. Considering both criteria, the process is classified as having middle (orange) suitability according to Table 4-4.

The qualitative analysis considers the criteria controllability, reactor type, space requirement, system complexity, research development, product quality and energy self-sufficiency.

Merging the quantitative and qualitative evaluations according to (Eq. 1) gives a score of 3.

$$\text{score}_{\text{tot}} = (1 * \text{score}_{\text{quant}}) + (3 * \text{score}_{\text{qual}}) = 1*0 + 3*1 = 3$$

Converting this score to the traffic light labeling gives an overall high (green) suitability of the distillation process for solar energy supply.

5 Results

For the semi-quantitative analysis, 30 processes from 7 industries were selected, resulting in 44 examined applications (see section Selection of processes4.1). This chapter shows the final assessment. Note that the evaluation of a specific process needs to be understood in relation to the other processes. In other words, if a process is assessed as low (red), it does not mean that the development of a solar reactor for this process is absolutely impossible. However, it indicates that based on the criteria used in this study, it is less suitable to develop a solar reactor for this process than for processes in the categories medium (orange) and high (green). Furthermore, the results show the suitability of a process in general (e.g. absorption) and not an industry-specific application (e.g. absorption of SO₂ in paper and pulp industry). Industry-specific applications were needed to collect relevant data, but the resulting information was combined to assess the process in general. If a lack of data for a specific process made the evaluation impossible, the process was excluded from the analysis.

Figure 5-1 depicts the results of the **quantitative analysis**. Six processes show a low suitability for a solar energy supply which is mainly due to high temperature requirements, namely (1) calcination, (2) converting, (3) depolymerization, (4) melting, (5) quenching and (6) smelting. Eleven processes have a medium suitability for a solar energy supply when considering the temperature level and market share including (1) bleaching, (2) cracking, (3) distillation, (4) drying, (5) dyeing, (6) oxidation, (7) polymerization, (8) precipitation, (9) roasting, (10) sterilization and (11) aerobic/anaerobic waste-water treatment (WWT). A total of 12 processes provide high suitability for solar energy supply: (1) absorption/desorption, (2) adsorption, (3) blanching, (4) cooking, (5) crystallization, (6) evaporation, (7) extraction, (8) nitration, (9) pasteurization, (10) photocatalytic oxidation, (11) electrolysis, and (12) fermentation. The process secondary metallurgy, which can be differentiated in machining, welding,

coating (galvanizing), tempering and surface treatment (carbonizing), was excluded because a more in depth analysis of each sub-process would be necessary to determine a suitability of the processes.

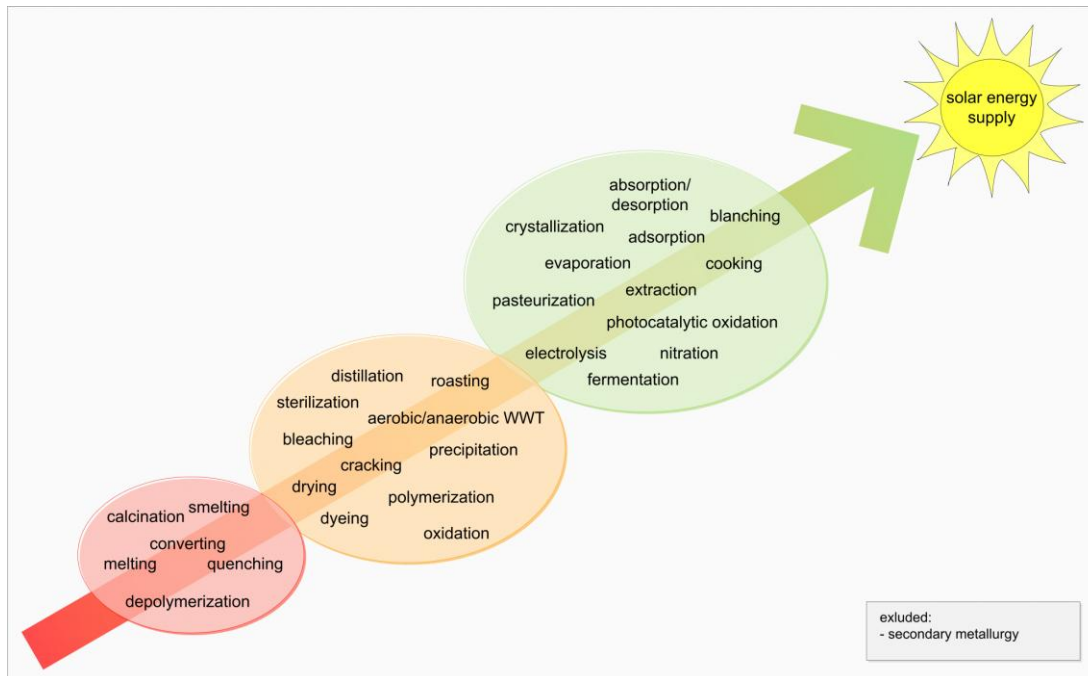
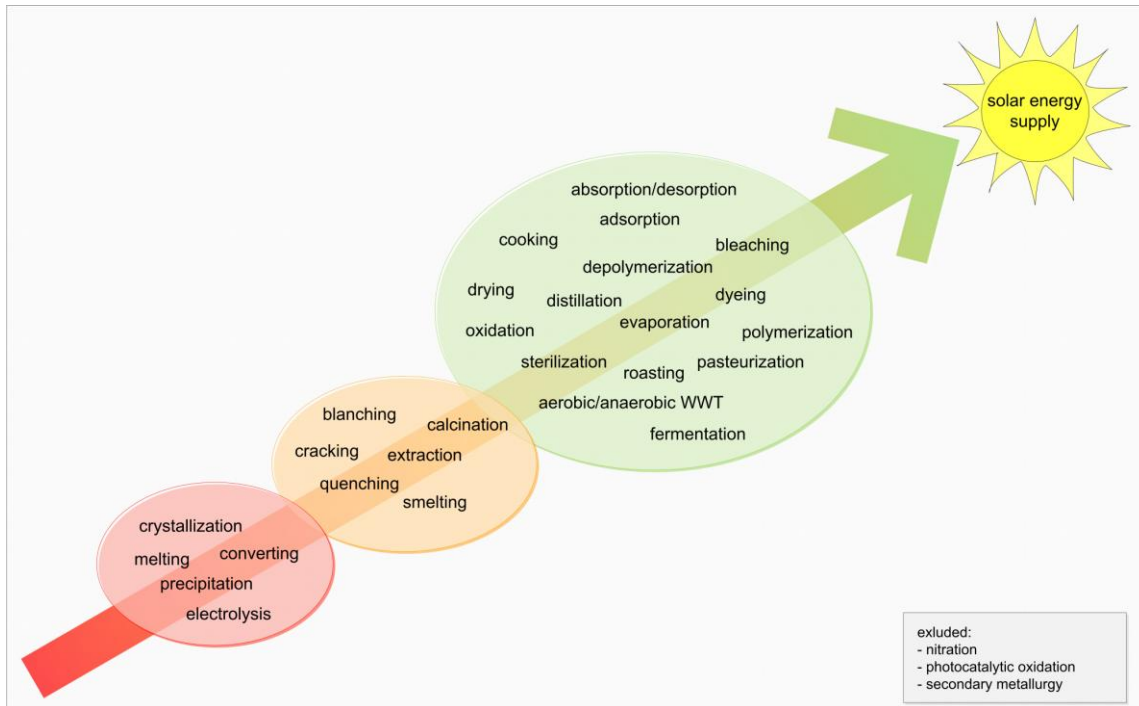


Figure 5-1: Results of quantitative analysis

(red = low suitability, orange = medium suitability, green = high suitability)

Figure 5-2 summarizes the results from the **qualitative analysis**. Five processes show a low suitability for a solar energy supply: (1) converting, (2) crystallization, (3) melting, (4) precipitation, and (5) electrolysis. Six processes show a medium suitability, namely (1) blanching, (2) calcination, (3) cracking, (4) extraction, (5) quenching and (6) smelting. The majority of the processes, namely 16 processes, show a high suitability for the solar reactor concept: (1) absorption/desorption, (2) adsorption, (3) bleaching, (4) cooking, (5) depolymerization, (6) distillation, (7) drying, (8) dyeing, (9) evaporation, (10) oxidation, (11) pasteurization, (12) polymerization, (13) roasting, (14) sterilization, (15) aerobic/anaerobic waste-water treatment (WWT) and (16) fermentation. The processes nitration and secondary metallurgy were excluded from the analysis because the available data was not sufficient. The photocatalytic oxidation is already an emerging technology in terms of the solar reactor concept and therefore not comparable to conventional processes. This process is excluded from the assessment as a stand-alone process, but its functionality is considered in the conventional oxidation process in the criterion *research development*.



*Figure 5-2: Results of qualitative analysis
(red = low suitability, orange = medium suitability, green = high suitability)*

Figure 5-3 summarizes the **final results** of the semi-quantitative analysis. Eight processes perform relatively poor for the implementation of solar energy supply: (1) calcination, (2) converting, (3) crystallization, (4) melting, (5) precipitation, (6) quenching, (7) smelting, and (8) electrolysis. Three processes show medium suitability: (1) blanching, (2) cracking and (3) extraction. Finally, 16 processes were assessed having a high suitability for solar energy supply: (1) absorption/desorption, (2) adsorption, (3) bleaching, (4) cooking, (5) depolymerization, (6) distillation, (7) drying, (8) dyeing, (9) evaporation, (10) oxidation, (11) pasteurization, (12) polymerization, (13) roasting, (14) sterilization, (15) aerobic/anaerobic waste-water treatment (WWT) and (16) fermentation.

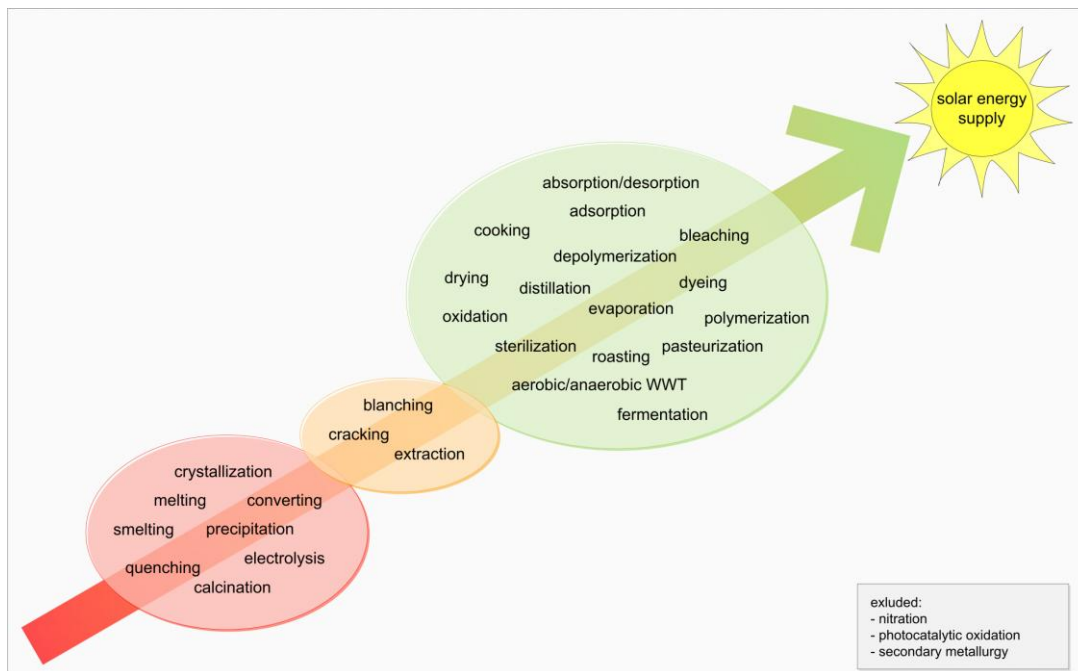


Figure 5-3: Final results of semi-quantitative analysis
(red = low suitability, orange = medium suitability, green = high suitability)

6 Discussion

The semi-quantitative analysis showed the economic and technical potential of solar reactors. The next step to bring solar reactors to the market is the development of solar reactor concepts. Below, the main challenges and opportunities are discussed.

Challenges lie in location-specific solar radiation and weather conditions, back-up systems, the choice of right design parameters and costs:

(1) Location-specific solar radiation and weather conditions are decisive for the implementation of solar reactors. The Global Horizontal Irradiance (GHI), which is defined as the sum of direct and diffuse solar radiation on a horizontal surface on earth and the Direct Normal Irradiance (DNI), the direct solar radiation (without diffuse radiation) on a surface perpendicular to the direction of the direct radiation, need to be considered before-hand. Long-term daily sums of GHI range from below 2.2 kWh/m²/d to above 7.4 kWh/m²/d. GHI hotspots are western South America, northern, eastern and southwestern Africa, the Arabian Peninsula and Australia with daily values of above 7.4 kWh/m²/d. DNI hotspots with daily averages larger than 7 kWh/m² can be observed in southwestern North America, western South America, southwestern Africa, northwestern Arabian Peninsula, Tibetan Plateau and Australia [56]. The challenge is, that suitable locations for industrial production sites and the availability of solar irradiance might not match.

(2) Back-up systems which buffer the volatile solar energy supply are needed. Due to the long-run volatility (months with low and high irradiance) and short-run volatility (within seconds, minutes, hours, days, weeks), the control of solar reactors should be set as semi-continuous. A semi-continuous

operating mode stems from the effort to accomplish a continuous process where possible in order to achieve energy efficiency gains based on process intensification principles when constraints of a volatile solar energy supply are present. If the solar energy supply is interrupted, two options are available. Either, the product is fully removed from the solar reactor and stored or the batch is finished with the help of the stored energy in the thermal mass of the solar reactor. The former case, depending on the solar reactor design, can require pumping the product back to the educt tank or using of an extra buffer tank. Pumping a partly-treated educt back in the educt tank would lead to an energy loss as the already heated product is cooled again and the process must restart from scratch. In contrast, if the partly-treated product is stored in an insulated buffer tank, the energy is not lost. But an additional tank makes the solar reactor system more complex. Additionally, removing a partly-treated product can require cleaning to ensure hygienic processing. In order to prevent an increase in system complexity and energy losses, designing the solar reactor with sufficient thermal mass might be a better solution. A more detailed investigation including the implications for educts and products, thermal mass, design parameters as well as the volatility of solar radiation is needed for a sound assessment of this option. In solar glass melting, this principle is already implemented. The melting vessel is put in a box with a large thermal mass to maintain the heat for time periods with low solar energy supply [45]. However, increasing the thermal mass can deal with short-term, but not with long-term fluctuations. Solar reactors need innovative back-up systems decoupled from fossil fuels.

(3) Design parameters such as material (properties), size, energy and mass transfer rates need to be selected optimally in order to simplify the solar reactor concept. The challenge is to use modularization to make solar reactors scalable and widely applicable.

(4) Costs for solar reactors have not been determined at the current stage of development. Operation costs are estimated rather small, as no fuel costs arise and the simple design of reactors minimize maintenance costs. Construction costs depend on the level of simplicity of the solar reactor's design and number of high-tech components.

Opportunities lie in recent developments regarding industry 4.0, synergies by combining multiple process goals, remote production and good investment prospects:

(1) Smart Control of solar reactors based on a Wireless Sensor Network (WSN), where the product quality (temperature, concentration, bacterial stock, etc.) is continuously monitored by smart sensors and where the control unit integrates weather forecasts can improve the performance and flexibility of solar reactors significantly. As the sensors are connected to the internet, control over large distances for remote production sites is possible. Implementing a WSN in solar reactors is in line with the Smart Logistics approach embedded in **industry 4.0**. In general, Smart Logistics is understood as the optimization of logistic processes through comprehensive use of information and communication technologies. This enables flexibility, adjustment to market fluctuations and brings a company closer to the needs of the customer [59]. Solar reactor concepts can use of the flexibility in production and storage enabled by Smart Logistics. Further opportunities considering market conditions and needs of the customer must be examined in the next step. Additionally, dependencies and system safety of Smart Logistics and its technologies need also to be investigated in regard to solar reactors and system safety must be ensured.

(2) Simultaneously using thermal and photocatalytic processes in one solar reactor generates **synergy** effects. Thus, different process steps (e.g. oxidation and separation in waste-water treatment) can be merged into one process which makes it simpler and more efficient.

(3) Restructuring industrial processes from **centralized to decentralized production** can make the use of solar reactors easier. This does not only support the approach of using educt storages instead of energy storages, but it can help to overcome difficulties originating from volatile energy supply as production capacities are downscaled and the production can be run in periods with low irradiance levels. Taking the pasteurization of milk as an example, decentralizing milk pasteurization would lower the processed capacity at one site. Pasteurization and the preceding homogenization of milk could be done at farms before being transported to an industrial unit for further treatment or packaging.

(4) Considering the economic status-quo of relevant industry branches, the **investment likeliness** is evaluated to be rather good for solar reactors. Solar reactors have a broad field of application in the industry. They can be implemented, among others, in the chemical and petrochemical as well as the food, drink and tobacco industry. These industry branches are the largest in terms of capital spending and R&D investments in Europe.

Figure 6-1 sums up the challenges and opportunities for the further development of solar reactors.

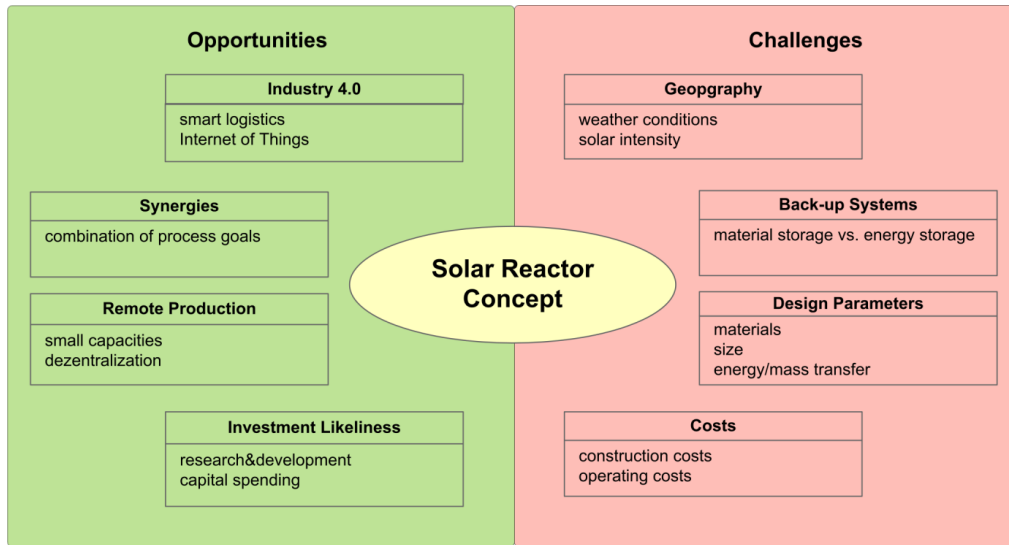


Figure 6-1: Opportunities (green) and challenges (red) of the solar reactor concept

7 Summary

This report contains a semi-quantitative analysis to identify industrial processes and reactors suitable for solar energy use with solar reactors. Processes were classified by a traffic light labeling system, where each color indicates the suitability of a process for the solar energy supply. In the semi-quantitative analysis, **30 industrial processes from 7 different industries were investigated based on extensive data collection.** The analysis showed that more **than half of the analyzed processes have a high suitability for solar energy use with solar reactors**, namely (1) absorption/desorption, (2) adsorption, (3) blanching, (4) cooking, (5) crystallization, (6) evaporation, (7) extraction, (8) nitration, (9) pasteurization, (10) photocatalytic oxidation, (11) electrolysis, and (12) fermentation. Ten percent of the processes have a medium potential for a solar energy use whereas a quarter of the investigated processes are not suitable for a solar energy use with solar reactors.

Overall, the analysis suggests that solar reactors have a high implementation potential throughout the industry. An analysis of potential applications in energy-intensive industries opened up new perspectives for relevant stakeholders. The solar industry, technology suppliers and the producing industry can now gain a better understanding of the benefits of solar reactors and favorable deployment conditions to embrace promising investment opportunities and support the development of innovative solar reactor concept.

8 References

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