KN12 - Solar Energy for the Aluminium Industry's Transition into the Future

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Abstract

In many regions, apart from energy efficiency measures, solar energy utilization will be the way to reconcile future environmental and economic requirements of aluminum production. In the paper we present, analyze and compare options for solar energy utilization, namely concentrating solar-thermal (CSP) and photovoltaics (PV). The analysis is regarding cost, performance, decarbonization rate, i.e. reduction of attributable greenhouse gas emissions, and land requirements. The focus is on applications for solar thermal collectors, specifically on enclosed parabolic trough collectors providing heat at up to 430 °C, including configurations featuring integrated thermal energy storage. They are compared to systems using PV-trackers, again including systems featuring thermal energy storage. A cost comparison is performed using a 'Levelized Cost of Heat' calculation, performance is assessed using the publicly available tool 'Solar Advisory Model' plus a validated in-house model for solar-thermal technologies.

Keywords: Aluminium production, Solar energy, Concentrated solar power (CSP), Photovoltaics (PV), Decarbonization.

1. Introduction

Aluminium is required for most future technologies, from PV module frames to lightweight cars. At the same time its production is very energy intensive. Thus, the industry is exposed to financial and regulatory risks from high energy costs and increasing costs for GHG emission rights [1]. Transforming the aluminium industry to a low-carbon sector is the challenge being faced.

One obvious option at suitable locations is a transition to solar energy. Several technologies are available to generate heat and power, which differ regarding cost, generation characteristics, options to integrate energy storage, land requirement and more.

While some companies may prefer to diversify and enter the market of power and heat generation, others want to keep focus on their core business. For the latter, power or heat / steam purchase agreements with owners and operators of renewable energy facilities may be the preferred option.

In the paper an overview is given over selected options for renewable energy provision including business models available, with a focus on enclosed parabolic trough systems, as they are the most cost-efficient option in many cases today, and PV systems, as they are widespread and very modular.

There are two major technical options to convert solar radiation into useful energy for technical processes:

a) Photovoltaics (PV), i.e. the direct conversion of radiation energy into electricity [2]. Electricity can then be converted to heat, if required.

b) Solar-thermal systems, i.e. the conversion of radiation energy into thermal energy. Optionally, in a subsequent step, thermal energy can be converted into electric energy by using turbines and electric generators [3].

If electricity is required, direct conversion using PV has the benefit of simplicity. If thermal energy is required, solar-thermal systems have the advantage of significantly higher conversion efficiencies and as a result, lower cost of heat, as will be shown below.

Another differentiator is the possibility of integrating energy storage: Integrating thermal storage into (solar-)thermal systems is straightforward and cost-efficient, integrating electric energy storage into PV systems is very costly and currently only a feasible option if electricity is the eventually desired energy form.

In the following, the term ‘solar fraction’ will be used. It is defined as ‘energy provided using solar irradiation as energy source’ divided by ‘total energy demand’, considering one calendar year for both values. To give an example: Assuming a process requires 438 GWh per year (continuous demand of 50 MW x 8 760 h/year), and a solar system provides 110 GWh per year of that demand, the ‘solar fraction’ is 110 GWh / 438 GWh ≅ 0.25, or 25 %.

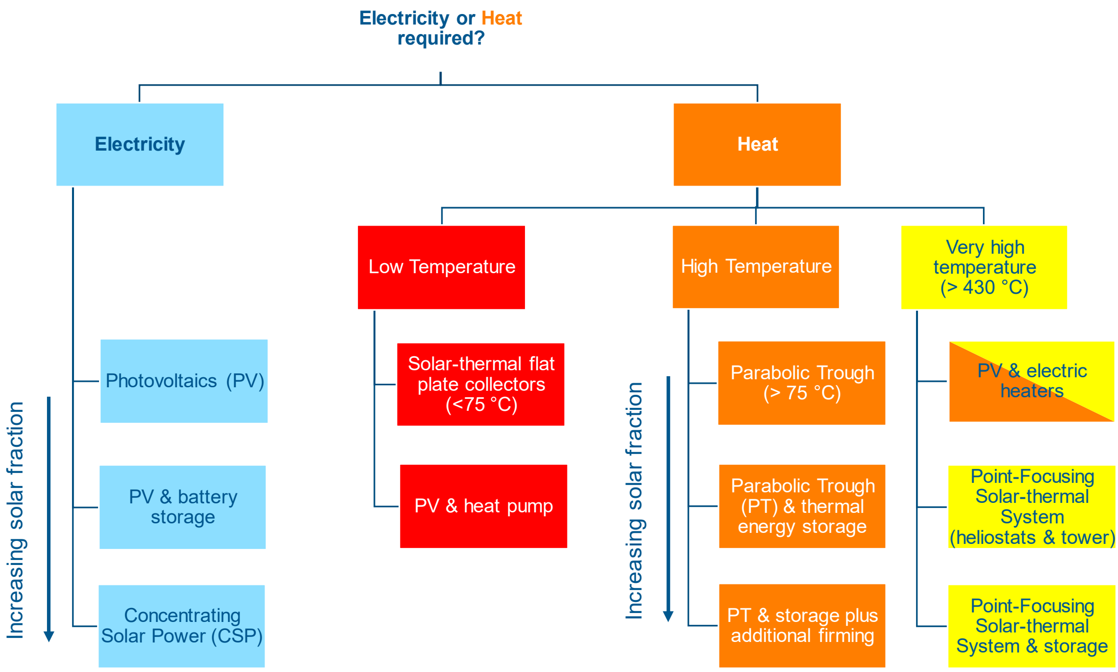

Figure 1. Selected options for provisioning of electricity or heat for industry.

Figure 1 gives an overview on options to provide electricity (left) or heat (right), with possible solar fraction increasing from top to bottom. This analysis focuses on high temperature heat (orange), i.e. systems employing parabolic troughs and/or PV and electric heaters with and without storage, respectively.

2. ‘Solarizing’ the Bayer Process

In the exemplary analysis, we will use the Bayer process for illustration.

2.1 Heat Demand

For the Bayer process, temperatures of the mixture of hot caustic soda solution and steam between 140 °C and 280 °C are required [4]. Pressure is not relevant for the process but defined by steam saturation pressure.

2.2 Technology Options

The option of burning fossil fuels will become less and less available. Alternatively, suitable steam can either be directly provided by a solar collector field, or it can be generated using heat from a thermal heat storage charged by a solar collector field. The first option is simpler and less costly, but it allows only to provide steam when the sun is shining. Thus, only a fraction of, say, 20 % of annual steam demand can be covered by solar energy if the industrial process is running continuously at 100 %. Achieving higher solar fractions is possible by enlarging the solar field and adding thermal storage capacity to it. 'Solar fraction' is a way to express decarbonization rate, because solar energy is characterized by very low attributable carbon dioxide emissions. The latter result almost completely from manufacturing of the systems, while operation is emission-free. 'Decarbonization' and 'solar fraction' are used synonymously here.

Several solar technology options exist to cover the heat demand, of which the following are analyzed here:

- PV plus electric steam generators
- PV plus electric salt heaters and molten salt thermal energy storage
- Solar-Thermal Collectors with molten salt thermal energy storage
- Solar Thermal Collectors with Direct Steam Generation

2.2.1 PV plus Electric Steam Generators

One option is to use electricity and electric heaters for provisioning of steam. Electricity can be a) completely purchased and provided via the grid, or it can be b) generated using a PV plant. Achievable decarbonization rates (= solar fractions) from PV are in the 20 % range. The electricity supply that cannot be covered by PV can be sourced from the grid, allowing high decarbonization rates. Obviously, this is only possible if enough 'green' electricity is available from the grid. Apart from this limiting factor, grid electricity including transport cost will be prohibitively expensive in almost all cases, therefore only the option using PV as electricity source is considered in this paper.

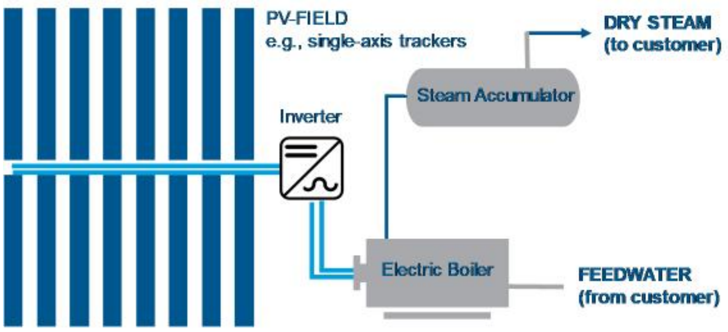

Figure 2. Schematic of solar steam generation using PV and an electric boiler (left) and a PV-tracker (right).

For the PV part, a state-of-the art single-axis tracker with bifacial modules and a ground coverage ratio (GCR) of 0.6 is assumed, which means a dense packing of the trackers. This high GCR is used to make the comparison with the densely packed enclosed trough systems (GCR ~ 0.7) more meaningful. In practice, tracker plants are often built with lower GCRs of 0.3…0.5 when enough land is available.

2.2.2 PV plus Electric Salt Heaters and Molten Salt Thermal Energy Storage

Figure 3 shows a configuration similar to the one shown in Figure 2, but it consists of a PV field powering electric salt heaters (instead of electric boilers) that heat molten salt in a storage tank. The hot salt (e.g. 450 °C) is then used to generate steam via salt/water-steam heat exchangers and circulated to a cold storage tank (e.g. 250 °C). By doing so, solar energy supply and provisioning of heat can be decoupled. Molten salt thermal storage has the benefit of scalability, low specific cost in for power and energy, and is a proven technology since many years, especially reliable and cost-efficient in the temperature range below about 450 °C.

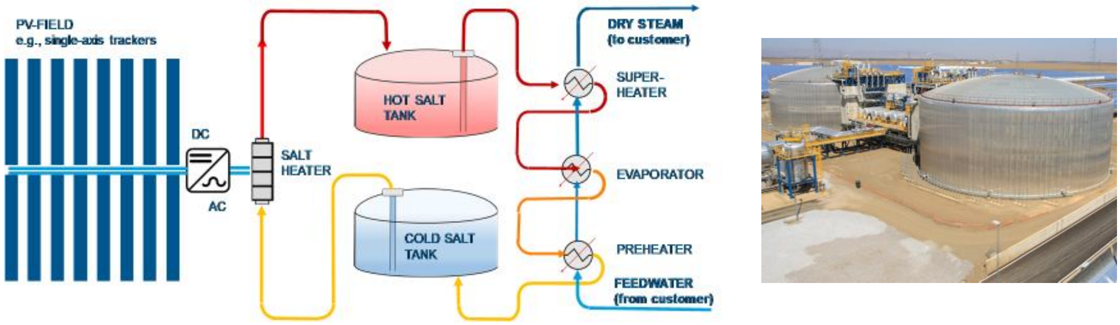

Figure 3. Schematic of solar steam generation using PV and electric salt heaters (left) and molten salt storage tanks (right).

2.2.3 Solar-Thermal Collectors with Molten Salt Thermal Energy Storage

The next option uses solar-thermal collectors, here of the parabolic trough type, to directly provide useful heat instead of first producing electricity which is then converted to heat. This approach has the advantage of a higher conversion efficiency - by a factor of about 3 - from solar radiation energy to heat: To give rough typical numbers: PV system efficiency of converting solar radiation to electricity is about 20 %, whereas for a high temperature solar thermal system the conversion efficiency is about 60 %, both at design point, respectively. Heat provided by the solar field is stored in large tanks.

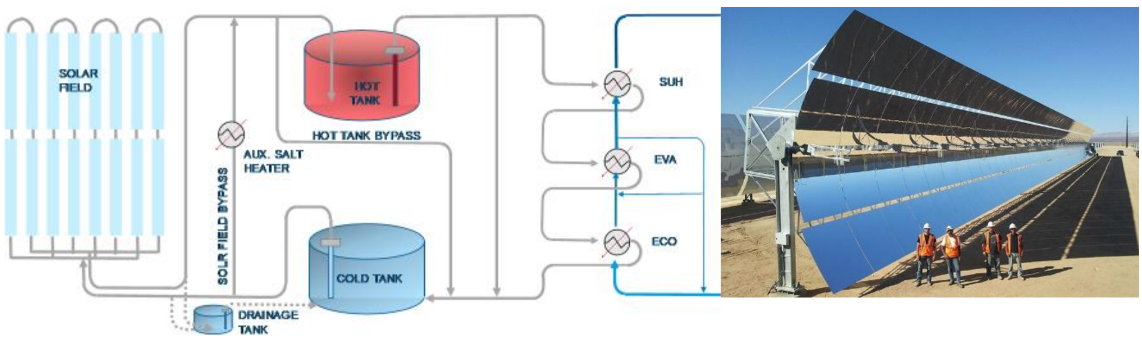

Figure 4. Schematic of solar field using molten salt as heat transfer fluid (left) and photo of a parabolic trough collector (right).

2.2.4 Enclosed Solar-Thermal Collectors for Direct Steam Generation

When land is scarce and the environment is harsh, there are benefits from installing the collectors in an easily cleanable enclosure and packing them densely. An example for such an arrangement is shown below for direct steam generation, i.e. without an intermediate heat transfer fluid.

Obviously, this design can also be used in combination with molten salt as heat transfer fluid and integrated thermal storage.

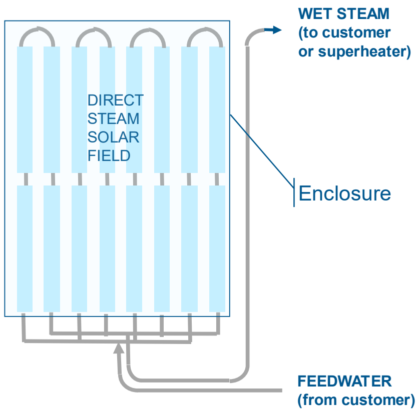

Figure 5. Enclosed parabolic trough collectors for direct steam generation (left: schematic, right: photo).

3. Analysis of Selected Options

The options to be investigated have been presented. Now, characteristic features, specific key cost and performance data are given. Table 1 shows a high-level comparison between concentrating solar thermal (CST) collectors and PV-Systems.

Table 1. Comparison between concentrating solar-thermal collectors and PV-systems.

	Concentrating Solar-Thermal	PV
Uses direct solar radiation	yes	yes
Uses diffuse solar radiation	No	yes
Solar-thermal efficiency	high	low
Requires flat land	yes	preferred

Meteorological conditions, mostly solar irradiation but also ambient temperature and wind speed impact energy output of these systems. Table 3 shows solar irradiation data for two sites with different solar irradiation characteristics used for the comparison to identify the impact of solar resource on performance and thus cost of heat or steam.

Concentrating systems like parabolic trough collectors use only Direct Normal Irradiance (DNI), i.e. solar radiation coming directly from the sun. DNI is evaluated assuming a receiver that always is oriented in a way that its surface normal points to the sun.

PV modules and flat plate collectors make use of direct and diffuse solar radiation. Direct and diffuse radiation together are called Global Radiation. Global irradiation is typically measured on a horizontal (fixed) plane, and then called Global Horizontal Irradiation (GHI). For performance calculations of tracking systems (parabolic troughs or PV trackers), relevant irradiation values are calculated for the respective angular orientation of the mirrors/modules for each analysed timestep. Analyses are performed using the US National Renewable Energy Laboratory's software tool SAM [5]. Levelized Cost of Heat are the figure of merit being evaluated using the methodology defined by the International Energy Agency's Task 54 [6], assuming an operation time of 20 years and an discount rate of 0 %.

Table 3: Solar irradiation data at selected reference sites.

		Site 1: KSA, Arabian Gulf	**Site2: USA, Southwest**
Annual DNI	[kWh/a]	1948	2678
Annual GHI	[kWh/a]	2120	2115
Seasonality* DNI	[-]	1.6	1.8
Seasonality* GHI	[-]	2.0	2.7
*Seasonality here is defined as the ratio between the highest and the lowest of monthly irradiation energy sums (DNI or GHI, respectively) of a typical meteorological year.			

Table 2: Cost and performance assumptions / input data for study.

Technology	**CAPEX**	**OPEX** [% of CAPEX]
PV-Tracker in MENA region	620 USD/kW_{DC}	1.5 %
Enclosed Parabolic Trough Collector *	137 USD/m²	1.5 %
Electric Boiler	150 USD/kW	1.5 %
Electric Molten Salt Heater	104 USD/kW	1.5 %
Molten Salt Thermal Storage *	55 USD/kWh	1.5 %
* medium value, cost reduction for larger systems considered		

4. Results

In Figure 6 results from an analysis of levelized cost of heat for selected solar options is shown for a site in Saudi Arabia. Costs (y-axis) are plotted versus decarbonization rate, i.e. the amount of thermal energy provided by the systems as a fraction of total demand. Demand is assumed to be constant 24/7 throughout the year. 30 % e.g. means that 30 % of the annual energy demand is provided by the solar (+storage) system. A discount rate of 0 % is used for this chart to show 'Simple Cost of Heat / Steam'.

According to Figure 6, (PV) systems without storage (black curve) can achieve up to about 30 % of decarbonization before costs increase prohibitively. By adding battery storage (grey line) larger decarbonization rates can be achieved, but costs are high. By storing energy in the form of heat either in molten salt storage tanks or in solid body storage systems (concrete, rock, ceramics etc.) costs can be reduced, but for decarbonization rates above the 50 % to 60 % range they still increase prohibitively. One reason for this behaviour is that while storing the energy itself is comparatively cost-efficient, charging such systems with electricity and later discharging them – in the case of solid body storage systems – with expensive heat exchangers is costly.

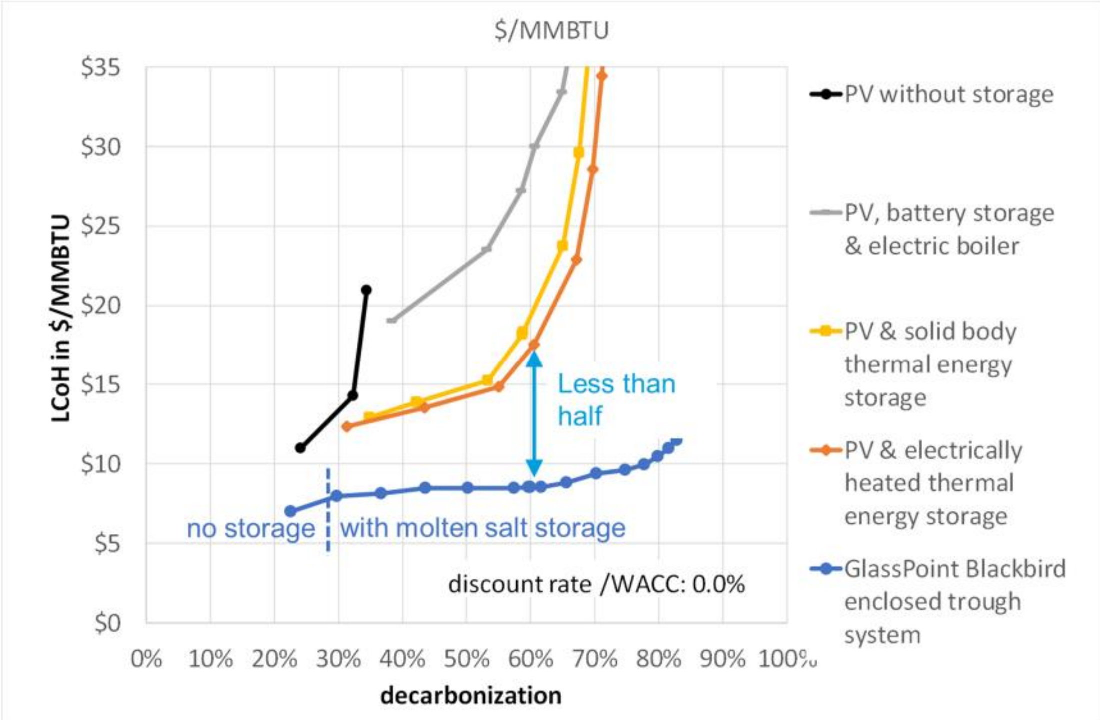

Figure 6. Results of comparative assessment of solar options for provisioning of heat for a site in Saudi Arabia at the Arabian Gulf.

A key result shown in the chart is that the most cost-efficient systems in general, and especially for higher decarbonization rates above, say, 50 %, are solar-thermal systems with molten salt energy storage, here the GlassPoint system with enclosed troughs. This can be explained as follows:

- Efficiency of directly converting solar radiation into heat (i.e. using solar-thermal collectors) with > 60 % is about three times as high as compared to first generating electricity (~ 20 %) and then converting electricity into heat.
- For decarbonization rates larger than about 20…30 % (site-dependent), storage systems are required. For charging and discharging of the storage, large and typically expensive electric heaters and/or heat exchangers are required. In the case of parabolic trough collectors with molten salt as heat transfer fluid, the absorber tubes are the heat exchanger for charging of the storage. As only very moderate pressure is required, these absorber tubes can be manufactured cost-efficiently.
- For steam generation, proven and compact molten salt/water-steam heat exchangers can be used, more efficient and less costly regarding investment and operation than the heat exchangers required to discharge solid body storage systems.

In a nutshell, the results don’t come as a surprise, but show what can be expected based on physics and cost data. One may argue that PV has gone through a decade long cost reduction and learning curve, resulting from an accumulated production of about one TW_{peak} as of 2023 [2]. Compared to that, concentrating solar-thermal systems, while proven technology since the 1990s, are only at the start of their cost reduction curve. Nevertheless, the advantage of a factor of three regarding efficiency overcompensates this production volume head start of PV, and with each solar-thermal process heat system built, this technology will also further advance down the cost-reduction curve.

Figure 7 shows specific land requirements of selected technologies to cover a given demand at an annual decarbonization rate of 50 %. Using PV in combination with thermal energy storage as compared to battery storage reduces land requirements, as the roundtrip efficiency of battery storage is significantly lower than that of thermal storage. Nevertheless, to meet the given target, the enclosed parabolic trough system requires less than half the land even as compared to the PV plus molten salt storage system. Again, this is not quite surprisingly, because the significantly higher solar-thermal efficiency of the parabolic trough system makes it also more land-efficient.

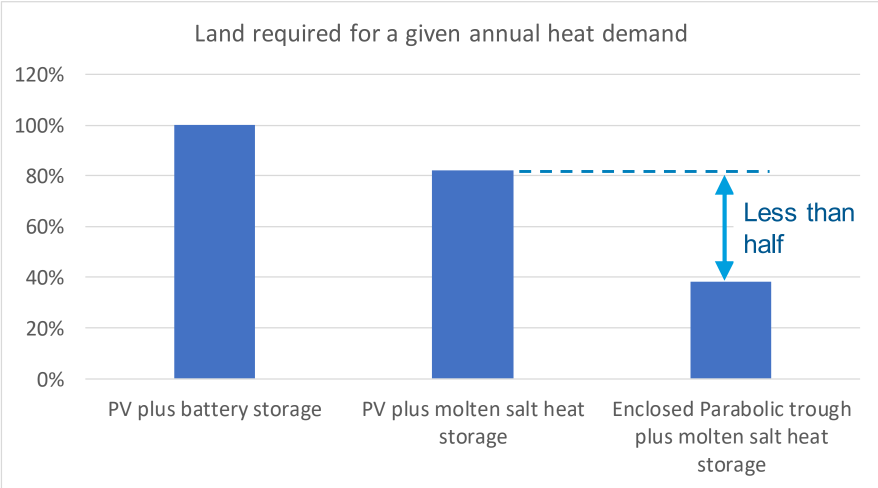

Figure 7. Land requirement of selected electric and solar-thermal systems to cover a given demand at a decarbonization rate of 50 % (example: Site in Saudi Arabia).

Note: The term 'Ground Coverage Ratio' (GCR) is used for PV system to define the ratio between PV module area and ground area. 100 % e.g. would mean that the ground is completely covered by PV modules. For this study, the PV systems have been designed and evaluated assuming an unusually high ground coverage ratio (GCR) of 0.6, and still the trough system requires less than half the land as compared to the PV plus molten salt storage system. Assuming a more standard GCR of 0.3 to 0.45 increases the difference accordingly to a factor of up to about four.

Given the above, some additional information on enclosed parabolic trough systems that have been identified as the most cost- and land-efficient option shall be provided:

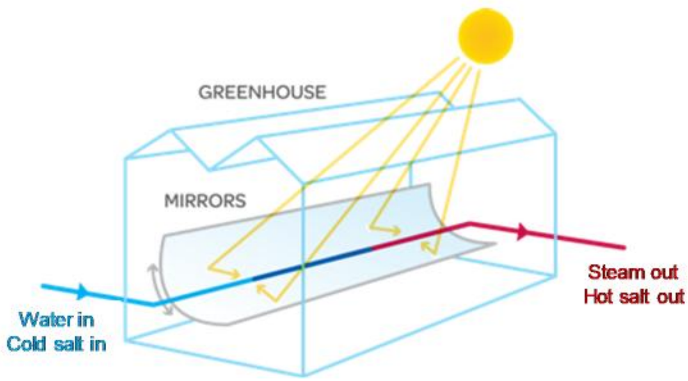

Figure 8. Functional principle of glasspoint enclosed parabolic trough collector [8].

Figure 8 shows a schematic of the GlassPoint system. The principle can be described as follows:

1. There are no solar panels in a GlassPoint system. Instead, large curved mirrors are suspended inside an agricultural "glasshouse".
2. The mirrors automatically track the sun throughout the day, focusing sunlight on a stationary boiler tube containing water.
3. The concentrated sunlight heats the water or molten salt to efficiently produce high-temperature steam or heat.

Figure 9 shows the inside of a GlassPoint collector. The principle is the same, no matter if steam is directly generated or salt is heated to allow for simple cost-efficient energy storage.

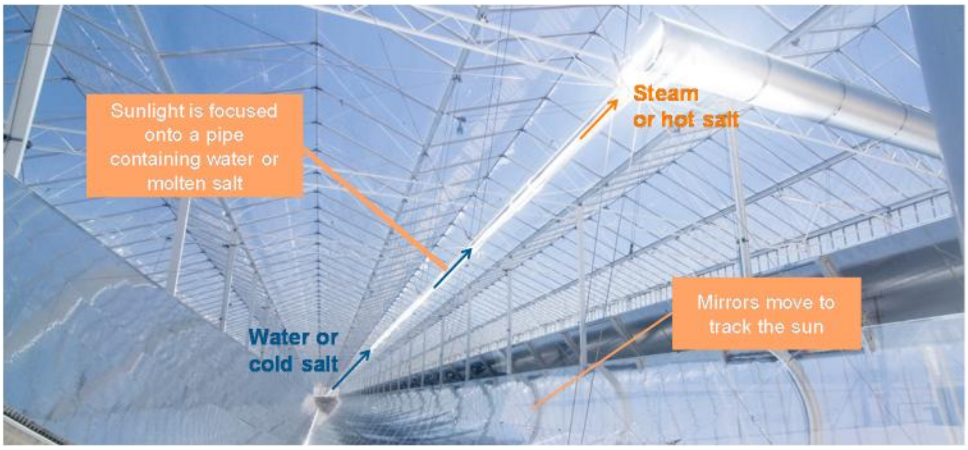

Figure 9. GlassPoint enclosed parabolic trough collector inside.

5. Additional Aspects

5.1 System Adaptation to Client Needs

There is no single solution that fits all. Thus, GlassPoint defines tailored systems for their clients using the building blocks 'collector for direct steam generation', 'collector for molten salt' and 'thermal storage' depending on the respective needs and local conditions. In special cases, PV systems can be used in addition to GlassPoint collectors to heat molten salt. This can make sense e.g. if topography favours PV, as there are systems available for hilly terrain.

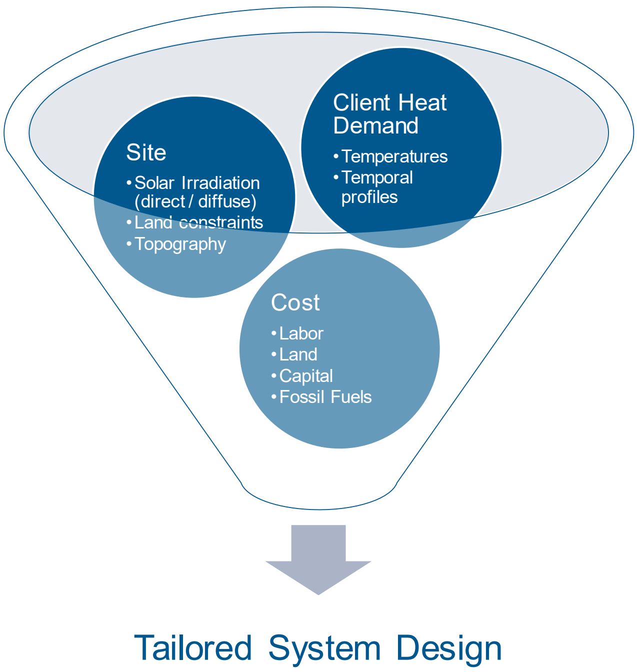

Figure 10. Funnel depicting information processed for a tailored system design.

5.2 Steam Purchase Agreement vs Self-operating the Solar System

Often companies prefer to focus on their core business. For them, ‘heat (or steam) purchase agreements’ with owners and operators of renewable energy facilities may be the preferred option.

For such clients, GlassPoint, the world leader and expert in designing, building and operating large-scale solar thermal systems, runs and operates the solar installations. The client only needs to sign a steam purchase agreement, hedging his risk of fossil fuel price increases while reducing the carbon footprint of his products. Should the client prefer to own and operate the solar-thermal system himself, GlassPoint is also ready to discuss and tailor this approach.

6. Summary and Outlook

The main findings are:

- Technologies are available enabling process heat decarbonization to a wide degree,
- For significant decarbonization rates, solar-thermal heat provision is more cost- and land-efficient than PV plus storage by factors of two and higher, respectively,
- Each site and each client is unique and therefore deserves a tailored solution. Tailored solutions can be designed and built from standardized proven building blocks.
- A ‘heat purchase agreement’ business model is available that caters client’s needs.

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