H2020-LC-SC3-2018-2019-2020
Solar Energy in Industrial Processes

FRIENDSHIP
Forthcoming Research and Industry for European and National Development of SHIP
Starting date of the project: 01/05/2020
Duration: 48 months

= Deliverable: D8.1 =

Environmental Mitigation Potential

Due date of deliverable: 31/07/2022
Actual submission date: 30/08/2022

Responsible WP: Andrea Leoncini, WP8, RINA-C
Responsible TL: Ingeborg Treu Røe, SINTEF Energi AS
Revision: V3.0

Dissemination level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 884213.

AUTHOR

Author	Institution	Contact (e-mail, phone)
Ingeborg Treu Røe	SINTEF Energy AS	Ingeborg.roe@sintef.no

DOCUMENT CONTROL

Document version	Date	Change
V1.0	05.07.2022	First version
V2.0	22.07.2022	After revision by WP-leader and task contributors
V3.0	30.08.2022	After revision by project coordinator

VALIDATION

Reviewers		Validation date
Work Package Leader	Andrea Leoncini	21.07.2022
Project Manager	Eleonora Alamaro	29.08.2022
Exploitation Manager	Andrea Toscano	30.08.2022
Coordinator	Valery Vuillerme	24.08.2022

DOCUMENT DATA

Keywords	SHIP, integration potential, environmental mitigation potential
Point of Contact	Name: Ingeborg Treu Røe Partner: SINTEF Energy AS Address: Statens Hus, Prinsens gate 1A, 7013 Trondheim Phone: +47 92688472 E-mail: ingeborg.roe@sintef.no
Delivery date	30.08.2022

DISTRIBUTION LIST

Date	Issue	Recipients
30.08.2022	V3.0	All partners + P.O.

DISCLAIMER

Any dissemination of results reflects only the authors' view, and the European Commission Horizon 2020 is not responsible for any use that may be made of the information Deliverable D8.1 contains.

Executive Summary

This report assesses the integration and environmental mitigation potential of the solutions for solar heat integration in industrial processes developed in the EU Horizon 2020 project, FRIENDSHIP. The assessments are carried out on four facilities partnering in the project: Moosburg, Tarragona, Nettgau and Mangualde. The facilities are spread out both geographically, from the North to South of Europe, and industrially, from chemicals to wood processing. Therefore, the results reflect the potential of the FRIENDSHIP solutions in a variety of locations and for a range of resources and energy-intensive industries, allowing an extrapolation to industries outside the FRIENDSHIP consortium.

The integration potential is evaluated using the solar heat yield and the solar heat fraction, meaning the solar heat yield over the total amount of fossil fuel consumed in a facility. The solar heat yield is calculated from the thermal efficiencies of the solar collector, the direct normal irradiation of the location and the total area available for the solar field. In the direct normal irradiation, we account for the solar power threshold under which the solar collectors herein do not operate. The integration potential assessment shows that the solar field's power threshold is particularly important for the northernmost facilities where the direct normal irradiation is below 0.9 MWh/m^2. Improvements in the solar collector efficiency and optimization of the power threshold lead to larger improvement in the solar heat yield in these areas compared to locations further south with higher direct normal irradiation. Consequently, continued improvement and optimization of the solar collectors to and beyond the 2 % improvement target of FRIENDSHIP are important to make integration in the northern parts of Europe attractive.

In the four facilities, all processes identified to be suitable for solar heat integration were producing steam or heating thermal oil. The heat demand in the steam and thermal oil processes ranged from 25 to 90 GWh, and was invariably larger than the solar heat yield even when the solar collector efficiencies were set to 100 %. Increased solar heat penetration is easiest achieved by increasing the area available to the solar field beyond what is typically accessible on roof tops. Such increase in the solar field area increases the CO_2 emissions during production and assembly of the solar field, but our assessments of the environmental mitigation potential, estimated as the reduction in CO_2eq emissions caused by the replacement of fossil fuel with solar heat, showed only a small penalty. Thus, the solar field area is a facile way to compensate for low direct normal irradiation and increase the solar heat penetration without significantly reducing the environmental mitigation potential.

One of the unique features of the FRIENDSHIP project is the integration of high temperature heat pumps together with the solar field to reach process temperatures up to 200°C. Including the high temperature heat pump in the integration potential assessment indicates that the complete heat demand of facilities located in the southern parts of Europe with direct normal irradiation above 0.9 MWh/m^2. For facilities in the northern part of Europe, the annual direct normal irradiation between 0.5 and 0.9 MWh/m^2 is too low to reach process temperatures towards 200°C. Nevertheless, the high temperature heat pump integration in the solar heat scheme is attractive in these regions because it can be used to reach medium process temperatures in the range around 140°C to 200°C with smaller solar field areas.

Based on the findings in the present report, we have identified a set of general recommendations that are meant to identify facilities within resources and energy-intensive industries in Europe where the FRIENDSHIP solutions have high integration and environmental mitigation potentials. Although the obtainable solar heat yield and process temperatures depend heavily on the area available for solar collectors and the location of the facility, determining the annual direct normal irradiation, there are three general features identifying suitable industries or facilities:

1. The facility has a substantial heat demand compared to its remaining energy consumption.
2. The heat is consumed first and foremost by producing steam or hot thermal oil.
3. The current energy source for the heat production is fossil fuel.

The requirements to available solar field area depend on the process temperatures and the facility's location. As a general rule, the solar field area requirements increase for locations further north in Europe and for higher process temperatures. For locations in the northern part of Europe – from Germany in the north to France in the South – we recommend that:

4. The process temperatures are below 200°C and the area available to solar collectors larger than what is typically accessible on roof tops.

In the southern part of Europe, process temperatures up to 200°C may be achieved with roof-top solar collectors, however, the electricity consumed by the heat pump is reduced with increased solar field area. Hence, both for process temperatures up to 200°C and for those between 200 and 300°C, it is beneficial if:

5. The area available to solar collectors is beyond roof-top area.

Finally, we note that improvements to the solar collector efficiencies will enable higher process temperatures at lower solar field areas, making the FRIENDSHIP solutions even more attractive in locations all the way from Germany in the north to Spain in the south of Europe.

Table of Contents

1 Introduction

In the period from 1990 to 2018, the greenhouse gas (GHG) emissions have increased by 50 %, mounting to 48.9 $GtCO_2e$ in 2018[1]. Energy production and consumption, mainly through combustion of fossil fuels, is responsible for 76.2 % of these emissions, out of which a third comes from process industries such as chemical and metal production (i.e., around 25 % of the total emissions). To reach the 2050 net zero emission target, it is paramount to reduce the GHG emissions from the industrial sector by shifting from fossil to renewable energy production. Solar thermal collectors are attractive for this purpose since more than 50 % of the energy consumed in the industrial sector is used for process heating or cooling. Thus, integrating solar thermal collectors with industrial processes requiring heating or cooling can significantly reduce the GHG emissions, and curb global warming.

Commercially available solar collectors are usually limited to process temperatures below 140-160°C. These operating temperatures are high enough to cover a large portion the heat demand of many processes. The solar heat fraction in dairy industries in India, where the process temperatures are below 180°C and mostly below 120°C, is for example found to be between 20 and 30 %[2]. In European resources and energy-intensive industries (REII), the heat consumption at temperatures below 100°C was estimated to 25 % of the total heat demand in 2012[3]. However, more than 20 % of the thermal energy is consumed in processes requiring medium temperatures (between 150 and 400°C) [4]. While unlocking this part of the thermal energy consumption increases the theoretical yield and environmental benefits of the solar heat solutions, the practical potential for solar heating in industrial processes (SHIP) at medium to low temperatures in Germany was evaluated to 3.4 % of the total heat demand[5]. This reduction compared to the estimated theoretical potential is caused by practical limitations when integrating the solar heat solutions in the industry, in combination with the relatively low total efficiency of the solar collectors especially in areas with medium to low solar irradiation such as in Germany. Additionally, the production and installation costs are high, making the time to return on investments exceeding 6 years[6], and limiting the installed annual capacity at the end of 2018 to 570 MW_{th} worldwide[7]. Consequently, steps to increase the temperature range available to solar heat solutions, as well as their efficiency and integration capability, must be taken to utilise the complete environmental potential of SHIP.

The EU Horizon 2020-funded project FRIENDSHIP therefore attempts to increase the temperatures delivered by the collectors to 300°C. Together with the development of absorption or ejection chillers providing cooling down to -40°C, this unlocks the substantial part of the industrial energy consumption which has hitherto been inaccessible to solar heat solutions. The temperature target will be reached through novel combinations of parabolic trough collectors (PTCs) from Absolicon, linear Fresnel reflectors (LFRs) from Industrial Solar and high-temperature heat pumps (HTHPs), as well as improvements to the efficiency of the collector absorbance coatings and heat transfer fluids. Since not all processes require operating temperatures as high as 300°C, two separate schemes are developed: one for operating temperature up to 200°C (SHIP200) and one up to 300°C (SHIP300). SHIP200 is based on the cheaper and more developed PTCs and couples these with an HTHP to reach 200°C. To achieve higher operating temperatures, the HTHP is replaced by LFRs. This does, however, increase the cost and required space of SHIP300 compared to SHIP200. In this report, we assess the integration potential of the FRIENDSHIP solutions as a function of both the technological improvements and the geographical location. The integration potential is evaluated in terms of the heat yield of a solar field compared to the annual thermal demand of a facility. Detailed assessments are performed for four out of five process industry facilities partnering in FRIENDSHIP, accounting for specific process requirements such as process temperatures, available area for the solar field and solar field integration points. The facilities cover a range of locations, from north to south on the continental Europe, and industry categories. Thus, the impact of the DNI, as well as process restrictions specific to different industries, are evaluated. Furthermore, the potential reduction in direct GHG emissions is estimated and compared to estimates of the GHG emissions associated with production and installation of the FRIENDSHIP solutions. Finally, we assess the FRIENDSHIP integration potential in industries outside the project's consortium, specifically in the sectors for resources and energy-intensive industries (REII) and sustainable process industries through resource and energy efficiency (SPIRE), based on the results from the partnering industries.

2 Solar field description and requirements

2.1 Solar field efficiency

The parabolic trough collectors (PTCs) and linear Fresnel reflectors (LFRs) used in the FRIENDSHIP project are manufactured and delivered by Absolicon and Industrial Solar, respectively. Since both the PTC and LFR are commercially available, their performance is evaluated. The thermal loss of a solar heat collector is described using:

$$\eta = \eta_0 - \frac{a_1\Delta T + a_2(\Delta T)^2 + a_3(\Delta T)^3 + a_4(\Delta T)^4}{DNI_a},$$

Eq. 1

where η_0 is the zero-loss efficiency, a_1, a_2, a_3 and a_4 are the thermal loss coefficients, $\Delta T = T_m - T_a$ is the temperature difference between the operating and ambient temperature and DNI_a is the annual direct solar irradiation. **Table 1** shows the thermal loss coefficients for the PTC and LFR[8,9].

Table 1. The thermal coefficients of the Absolicon PTCs and Industrial Solar LFRs.

Thermal coefficients	Zero-loss efficiency, η_0 (-)	a_1 (W/m^{2}K)	a_4 (W/m^{2}K^4)
PTC	0.766	0.368	0.0
LFR	0.686	0.033	1.48e-9

The annual heat yield of a solar field is the product of the field's efficiency, the total aperture area and the solar irradiation. Since the heat yield is found to correlate linearly with the direct normal irradiation (DNI)[10], an average, annual DNI, DNI_a, is estimated and used herein. On the other hand, the operation of the solar collectors is limited by the solar power. That is, the collectors are not operating when the DNI power is below a threshold, DNI_{thres}. Considering the thermal efficiency, the sum of the DNI power exceeding the threshold throughout a year, DNI_{thres}, and the solar field's aperture area, A, the annual heat yield from the solar field is given by:

$$E = \eta \cdot DNI_{thres} \cdot A.$$

Eq. 2

The current threshold for the PTC and LFR of Absolicon and Industrial Solar is around 300 W/m^2. FRIENDSHIP aims to increase the solar absorbance and heat transfer with 2 %, reducing the threshold to 294 W/m^2, and increasing the zero-loss efficiency η_0 to 78 %. The DNI_a, DNI_{thres} and A are specific for different locations and detailed for the different facilities in section 3.

2.2 SHIP200, SHIP300 and combined SHIP schemes

Both Absolicon's PTCs and Industrial Solar's LFRs have input and output temperature requirements limiting their application. The PTCs have a maximum output temperature at around 160°C. The LFRs can give output temperatures towards 300°C but have a minimum input temperature of 160°C. To provide temperatures at 200°C and 300°C, necessary for REII, three different combinations of the solar collectors are proposed in the FRIENDSHIP project.

2.2.1 SHIP200

Firstly, SHIP200 combines the PTCs with high temperature heat pumps (HTHPs) developed within the project to reach 200°C. That is, the HTHP lifts the temperature from 160°C to 200°C. This involves a reduction in the overall efficiency of the scheme compared to a stand-alone PTC scheme. However, the performance of the total system is still uncertain as it has not been finalized and validated at the time of this report. Herein, we have therefore performed two different analyses; one where the PTCs are assumed to be capable of reaching 200°C, and one where the power, P, required to lift the temperature from the solar field output temperature, T_C, to the process temperature, T_H, using the HTHP is estimated as:

$$P = \frac{P_{ev}}{COP - 1},$$

Eq. 3

where $COP = \alpha \cdot COP_{carnot} = \alpha \cdot \frac{T_H}{T_H - T_C}$ is the real coefficient of performance of the heat pump, α is the efficiency compared to the Carnot cycle, and P_{ev} is the evaporator power. In the estimations herein, we assume that $\alpha = 50\%$ and that the evaporator power is equal to the solar field power.

We notice that, according to **Eq. 1**, the assumption in the first case (*i.e.* no HTHP integrated) involves a slight decrease in the solar collector efficiency compared to solar field output temperatures at 160ºC, which is the solar field output temperature in the second case. In addition, we notice that in the second case, the simplified model of the HTHP does not consider the limitations of the HTHP. That is, we assume herein that the temperature difference, $T_H - T_C$, is unlimited, and only affects the COP of the HTHP, and that the HTHP operates stably under variable supply temperatures, T_C.

2.2.2 SHIP300 and combined SHIP

Secondly, the SHIP300 scheme is designed to reach temperatures up to 300ºC using the LFRs alone. The input temperature must be above 160ºC. Thus, a third scheme is necessary to reach temperatures above 200ºC from below 160ºC, combining the PTCs with the LFRs. If this combined SHIP scheme is used, the efficiency is taken as the average of the PTC and LFR efficiencies, and they are assumed to take up 50 % of the available area each.

3 Industry description and process requirements

The five process industry facilities that are partnering in the FRIENDSHIP project and subjected to the detailed integration potential assessment herein, are spread both geographically from the north to the south of Europe and thematically from the chemical to the wood-processing industry. The geographical location of the facilities is displayed in **Figure 1** along with the annual DNI, where blue is low (DNI < 300 W/m^2) and red is high (DNI > 1500 W/m^2). The DNI is estimated by Solargis in the Global Solar Atlas. Clariant owns three chemical facilities in Moosburg, Gendorf and Tarragona, while the two wood-processing facilities in Nettgau and Mangualde belong to Sonae. The process requirements vary from one industry to another, but also internally within an industry. In the following, we describe the process specifications and requirements that are considered in the integration potential assessment for each facility. These specifications are summarized in **Table 2**.

Figure 1. European map over the facilities in Moosburg, Gendorf, Tarragona, Nettgau and Mangualde. The colour coding corresponds to the annual DNI; blue is low (<300 W/m^2) and red is high (>1500 W/m^2)

Table 2. Summary of the specifications of the systems at the facilities of Clariant and Sonae.

		Moosburg	**Gendorf**		**Tarragona**	**Nettgau**	**Mangualde**
DNI (MWh/m^2)		1.112	1.115		1.72	0.953	1.847
DNI$_{300}$ (MWh/m^2)		0.643	0.667		1.559	0.357	1.711
DNI$_{294}$ (MWh/m^2)		0.688	0.685		1.586	0.43	1.72
Available area (m^2)		7000	2244		9800	38 295	5000
Annual CO_2 emissions (tonnes)		37 220	-		7 070	23 086	- *
Annual fossil fuel energy consumption (GWh)		215.4	-		40.2	101.3	58.5 **
Steam / thermal oil description	**Production mode**	On-site	External		On-site	On-site	On-site
	Boiler type	Steam	Steam		Steam	Thermal oil	Thermal oil
	Boiler fuel	Natural gas	Natural gas		Natural gas	Natural gas	Biomass
	Pressure (bar(g))	16	20	3.9	13	6	5
	Inlet temperature (°C)	10 #	150	60	60	140	160
	Outlet temperature (°C)	240	240	170	200	240	280
	Boiler annual energy consumption (GWh)	50.4	116.5	90.6	26	83.5	47.9
Solar heat concept (SHIPXXX)		Combined	300	200	Combined	300	300

*Mangualde does not use fossil fuels, but biomass to power its boilers. Therefore, the facility does not report on CO_2 emissions, and they are not tracked.

**Although Mangualde uses biomass instead of fossil fuel, some of the biomass is purchased from forestry and may still have an environmental/biological footprint. The solar heat yield is compared to the estimated energy consumption sourced from the purchased biomass.

#River temperature is around 10 °C, however, waste fumes are used to increase to steam boiler water inlet temperature to 180 °C. Integrating the system with solar heat reduces the amount of waste fumes and decreases the inlet temperature,

3.1 Clariant chemical facilities

Clariant's facilities handle and process chemicals for a wide range of applications from food industry to foundry. Although the three facilities operate with different materials and precursors and produce different end-products, the handling and processing are similar in that pressurized steam is used both directly in the processes and for process heating. These steam networks are identified as appropriate for integration with the solar heat solutions. Detailed below are the requirements for the steam networks (pressure, temperature, etc) as well as the external conditions (DNI, fossil fuel consumption, etc) at the different facilities.

3.1.1 Moosburg

Clariant's facility in Moosburg, which is located north of Munich and has an annual DNI of 1.095 MWh/m^2, handles and processes bentonite. Steam is used partially for drying of bentonite together with heated air, but mostly for processing. It is consumed in the process, and there is no return condensate. The steam is delivered at an average pressure of 16 bar(g) and around 240^{o}C. Downstream, the steam line is separated into two, and water is injected into one of the lines to reduce the pressure to an average of 2.5 bar(g). Even though there is no return stream in the steam network, the inlet water to the steam boiler is provided at 180^{o}C since waste exhaust gas is used to heat the inlet water, which originates from a well, from around 10^{o}C. **Figure 2** shows the monthly steam production energy demand alongside the average monthly DNI. The energy demand includes the boiler efficiency, which is estimated to 90 %. The steam boiler is fired with natural gas and does not only deliver steam to the processes at Clariant's facility, but also to the rest of the industrial park which the facility is a part of. Since the air used in the drying processes is also generated using natural gas fired heaters, the annual consumption of natural gas exceeds 200 GWh. The resulting direct emission of CO_2 is estimated to 37 220 tonnes. An overview of the facility specifications is found in **Table 2**.

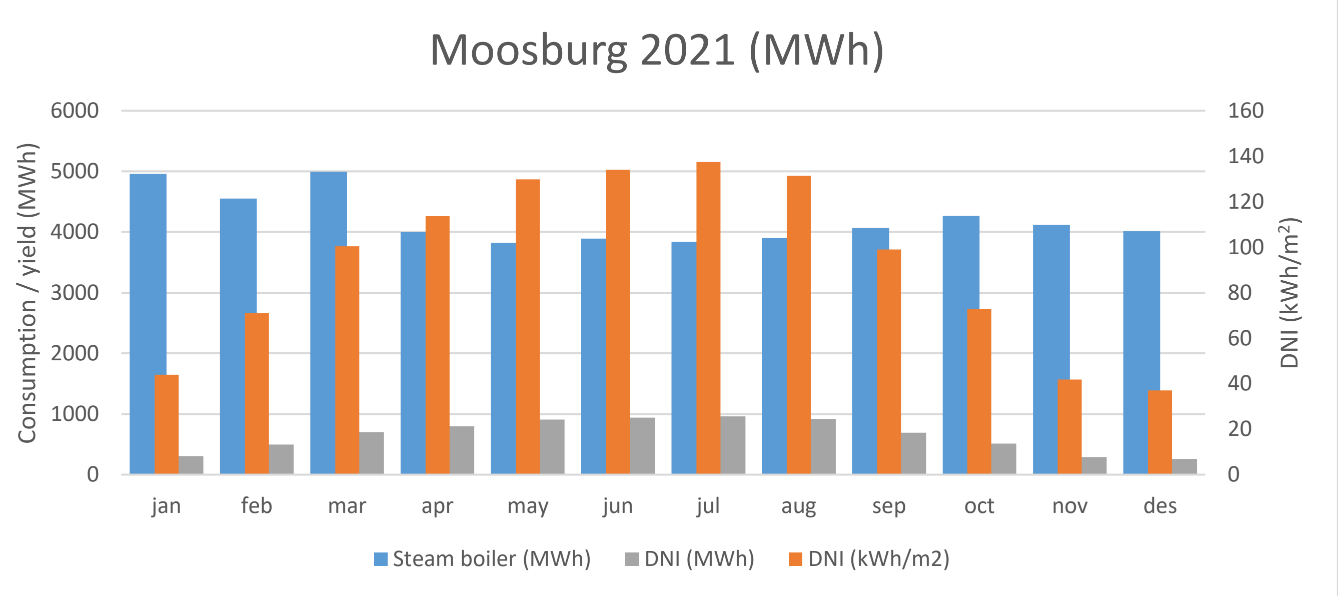

Figure 2. Monthly energy consumption in the steam boiler, along with DNI per unit area and DNI for the total solar field area for Moosburg in 2021.

3.1.2 Gendorf

Gendorf is a south-eastern German city with an annual DNI of 1.096 MWh/m^2.[11] As opposed to the other two Clariant facilities, the facility in Gendorf has very limited roof area available for the solar field. Additionally, the facility does not produce steam itself, but receives it from an external provider. The facility have legal obligations towards the external provider, which together with the limited space renders the solar heat integration difficult. Design for a solar heat system at Gendorf was made earlier in the FRIENDSHIP project, and an assessment of its performance showed that less than 1 % of the steam heat can be replaced by solar heat. For these reasons, Gendorf is excluded from the assessment.

3.1.3 Tarragona

The facility in Tarragona is the southernmost of the Clariant facilities. It is located on the north-east coast of Spain with a substantially higher annual DNI compared to the Moosburg and Gendorf facilities. The facility produces polymers, surfactants and speciality chemicals through reactions such as ethoxylation, propoxylation and polymerization. Steam, used directly in the processes and for process heating, is produced at an average pressure of 13 bar(g) and around 200^{o}C. The steam network is partially open (i.e. there is only 40 % return steam stream to the steam boiler), but process waste fumes are used to heat the steam boiler inlet water from ambient temperatures to around 60°C. Since many of the process reactions are exothermic, the cooling demand at Tarragona is higher than at Moosburg and Gendorf. Nevertheless, the heating demand is still higher than the cooling demand and exceeds the annual DNI. This is illustrated in **Figure 3**, showing the monthly energy consumption for the steam production, the average monthly DNI of the location and the average monthly DNI on the area of 9800 m² available for solar collectors. The overall, annual energy consumption for steam production to the network is 26 GWh (this includes an estimated efficiency of the steam boiler at approximately 95 %). The total annual natural gas consumption is 3.811 million Nm³, corresponding to approximately 40 GWh_{th} and an annual direct CO_2 emission of 7 070 tonnes.

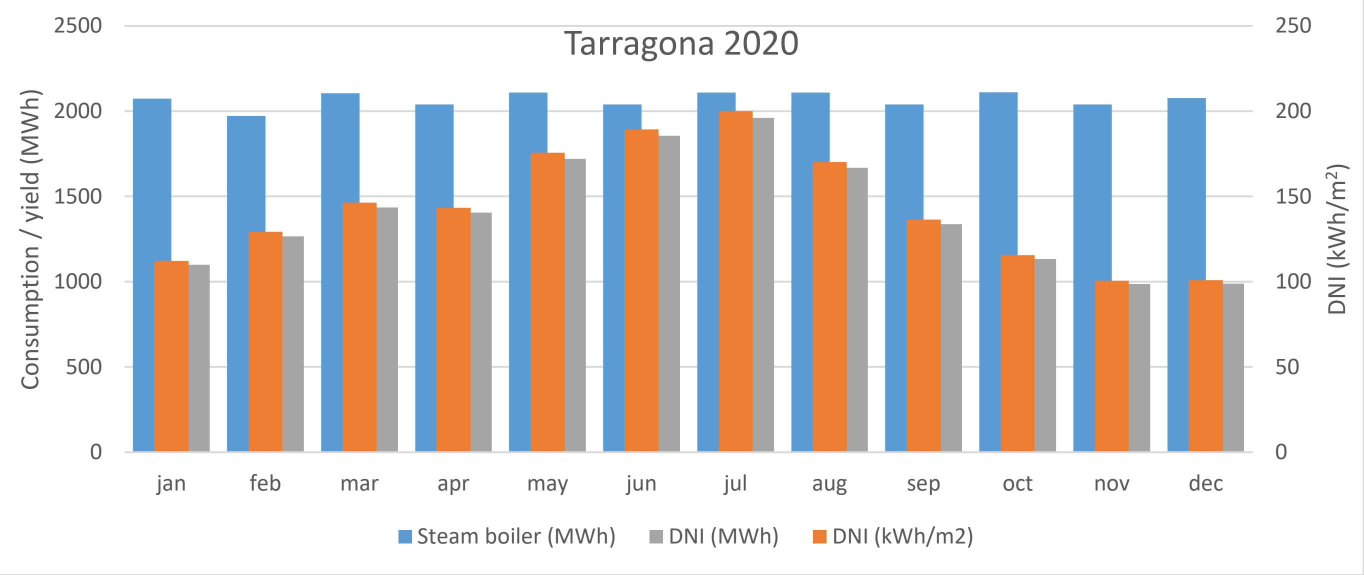

Figure 3. Monthly energy consumption in the steam boiler, along with DNI per unit area and DNI for the total solar field area for Tarragona in 2020.

3.2 Sonae wood-processing facilities

Sonae has two wood-processing facilities: in Nettgau and Mangualde. Both facilities manufacture wood-based panels. The panels are pressed using heat and pressure provided by thermal oil boilers. The facilities also have steam networks providing heat and pressure to some of the steps in the manufacture stream, however, the thermal oil system was found to be the most appropriate system for interfacing with solar heat.

3.2.1 Nettgau

Sonae's facility in Nettgau, which lies north in Germany, has an annual DNI of 0.953 MWh/m², ranging lowest of all the facilities considered in this assessment. However, the area available for solar collectors at 38 295 m² is substantially higher than at the other facilities, counteracting the low areal DNI. The thermal oil boiler supplies thermal oil at 240 °C with a return temperature at 140 °C, making the SHIP300 concept appropriate for the facility. The thermal oil system drives the major presses in the facility and consumes annually around 80 GWh of natural gas, accounting for 80 % of the natural gas consumption and 15 % of the total energy consumption in the facility.

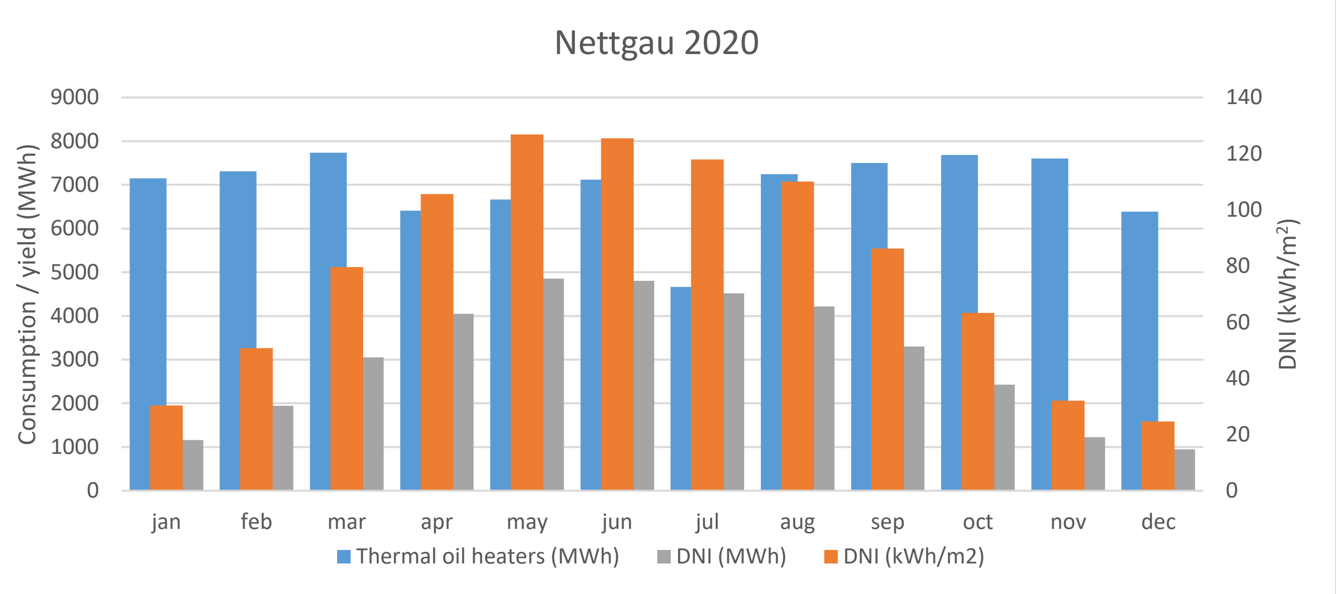

Figure 4. Monthly energy consumption in the thermal oil heater, along with DNI per unit area and DNI for the total solar field area for Nettgau in 2020.

3.2.2 Mangualde

Mangualde lies in the center of Portugal with an annual DNI of 1.855 MWh/m^2. Sonae's facility lies slightly outside the city center and has potentially both rooftop and ground area available for solar collectors. The facility produces wood-based panels using heat and pressure. Biomass generated boilers heat thermal oil to 280°C and around 5 bar, driving the precompressors and presses. Biomass is also used to fire steam boilers for the defibrators used in the fiber production. The biomass comes from process residues and residual forest, which singles the facility out as the only facility not having fossil shares in its energy portfolio. Biomass can have an environmental footprint, and a LCA should be performed to assess whether solar heat produces less emissions than the biomass. This is outside the scope of the work presented here, but it is likely that the solar heat option will have a larger footprint, particularly because over 80 % of the biomass in this case stems from process waste and residuals. In addition, the use of biomass as fuel means that Mangualde is not required to monitor its CO_2 emissions under the EU ETS[12]. Thus, we have excluded the facility from the environmental mitigation potential assessment described later. We perform the integration potential assessment for Mangualde similar to the other facilities.

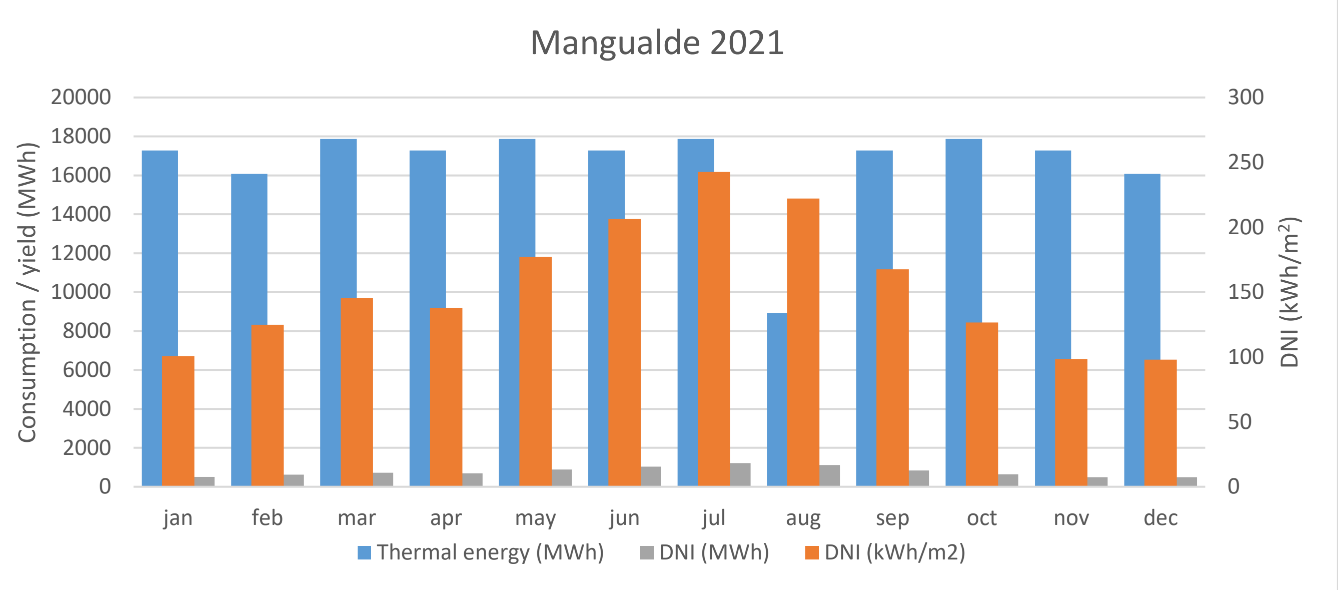

Figure 5. Monthly energy consumption in the thermal oil heater, along with DNI per unit area and DNI for the total solar field area for Mangualde in 2020.

3.3 Resource and energy intensive industries in Europe

Europe has a growing market for resource and energy-intensive industries (REII) and a high focus on sustainable process industries through resource and energy efficiency (SPIRE). The European chemical sector, to which Clariant's facilities belong, is for example the second largest producer in the world, only second to China[13]. A multitude of companies are spread across Europe, displaying a diversity both in size and scope; from the largest companies with annual turn-over at almost 90 billion EUR[14] to the smallest at around 4 million EUR[15]. The activity is highest in Germany, but also France, Italy and Spain have total turnovers above 40 billion EUR[13]. The diversity is also reflected in the range of process temperatures; around 30 % of the total heat consumed is spent in processes at 100-400°C, almost 50 % is consumed above 400°C and the remaining 20 % at temperatures below 100°C[3]. For the pulp, paper and wood sector, the picture is similar, with facilities ranging from large to small-scale production, and at varying process temperatures[16].

Since location, energy consumption and process temperatures will vary from facility to facility, it is challenging to directly transfer the process requirements from the facilities studied in this report to their respective market sectors. Instead, we will perform a qualitative assessment of the transferability of our results and develop some guidelines for industries and facilities where the FRIENDSHIP solutions may have high potential for increasing the renewable energy penetration and reducing green-house gas emissions.

4 Integration and environmental mitigation potential methodology

The integration potential is assessed as the share of solar heat in the energy portfolio of the facilities. The SHIP scheme of the solar field depends on the requirements of the facility, and affects the overall efficiency of the solar field, calculated according to **Eq. 1**, slightly. This influences the solar heat yield, calculated according to **Eq. 2**, and thus the share of solar heat, or solar heat fraction, according to **Eq. 4**. For the SHIP200 scheme, relevant for Moosburg and Tarragona, additional complexity is added due to the integration of the high temperature heat pumps (HTHPs). Since the HTHPs are not finalized and validated at the time of this work, their contribution is disregarded for the main part of the analyses herein. However, a simplified heat pump model is used to estimate the reduction in overall energy consumption for producing steam compared to the current cases (see section 2.2 for further details), indicating the influence of the HTHPs on the integration potential of the FRIENDSHIP solutions.

The environmental mitigation potential is quantified as the CO_2 emission reduction corresponding to the integration of solar heat, but solely for the SHIP schemes where the HTHPs are disregarded. The corresponding annual emission reduction is estimated as shown in **Eq. 6**.

Four scenarios were identified to shed light on both the current and future integration and environmental mitigation potential for the FRIENDSHIP solutions. **Table 3** details the varying aspects included in the different scenarios.

Table 3. Definitions of the four different scenarios.

Aspects included in the assessment	**Scenarios**			
	1	**2**	**3**	**4**
Processes available for SH	✓	✓	✓	✓
DNI & total available area	X	✓	✓	✓
SH current efficiency (DNI > 300 W/m^2, collector area, current thermal efficiency)	X	X	✓	X
SH target efficiency (DNI > 294 W/m^2, collector area, future thermal efficiency)	X	X	X	✓

In scenario 1 the theoretical potential for the exploitation of solar heat is defined by identifying all the processes that can be supplied by solar heat. These processes (identified in collaboration with the facility's energy managers) usually include either steam production or heating of thermal oil. In scenario 2, the maximum potential of solar heat supply is defined by accounting for the DNI of the facilities' location, in addition to the total available area for the solar field. In this scenario, the thermal efficiency of **Eq. 1** and the area utilization are assumed to be 100%. The actual solar field efficiencies, related to the power restrictions at 300 W/m^2 and the thermal efficiency calculated as in **Eq. 1**, is accounted for in scenario 3. Lastly, scenario 4 takes the target efficiencies of FRIENDSHIP into account, that is a 2% improvement to a power threshold at 294 W/m^2 and a thermal efficiency of 78%.

Scenarios 1 and 2 are the practical and theoretical limiting cases for the benefits possible to achieve with the FRIENDSHIP solutions. In the extreme where the available solar field area is unlimited, the processes possible to integrate with solar heat (i.e., scenario 1), limit the solar yield. However, in case of limited available solar field area, the DNI will usually be the restricting factor. Scenario 3 defines the solar yield achieved with the current technology, while scenario 4 describes the solar yield possible if the efficiency targets of FRIENDSHIP are reached.

5 Results and discussion

5.1 FRIENDSHIP integration potential

5.1.1 Process energy consumption and solar heat yield

Figure 6 shows the Sankey diagrams for scenario 1 and 2 for Moosburg, Tarragona, Nettgau and Mangualde, respectively. The figure visualises the upper bounds for the share of fossil fuel that can be replaced with solar heat.

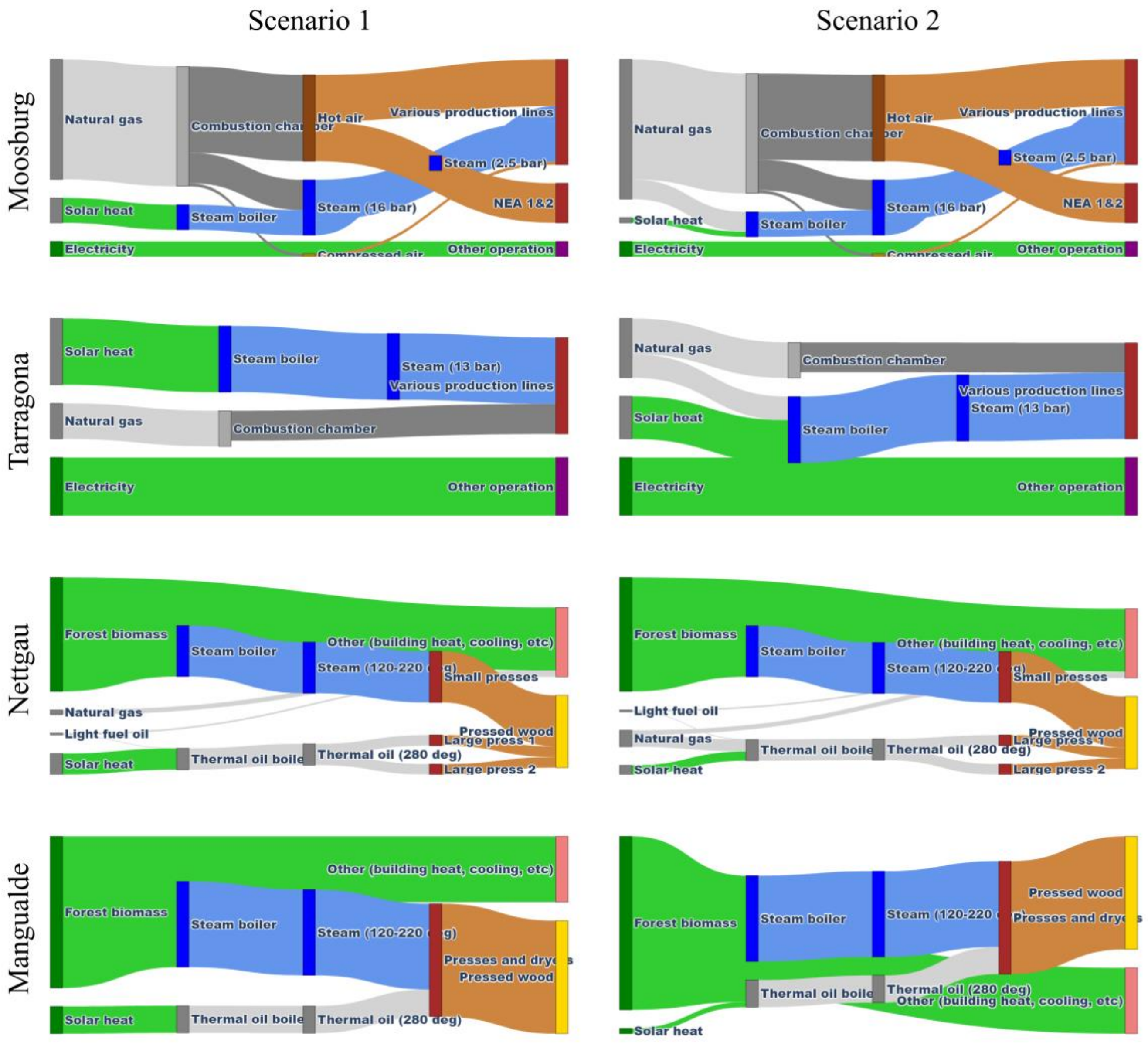

Figure 6. Sankey diagrams showing the energy streams for Moosburg, Tarragona, Nettgau and Mangualde for scenario 1 and 2.

We see that in all facilities, scenario 2 provides the smallest solar heat share, meaning that the DNI and the available area are the limiting factors. This is because the processes identified as practically possible to integrate with the FRIENDSHIP solutions, steam production and heating of thermal oil, represent a considerable part of the heating demand in the facilities, and both the available area for the solar field and the DNI are restricted. To maximize the theoretical integration potential of the FRIENDSHIP solutions, the heat yield of scenarios 1 and 2 should match. This would require an increase in the available area for the solar fields of 480 %, 155 %, 228 % and 520 % for Moosburg, Tarragona, Nettgau and Mangualde, respectively, covering a total area of more than 160 000 m^2. Recall that the solar field efficiencies are not considered in scenario 2. **Table 4** quantifies the solar heat fraction of all four scenarios from **Table 3**, and for each facility. The solar heat fraction, f_{solar}, is given by:

$$f_{solar} = \frac{E}{E_{fossil}},$$

Eq. 4

where E is the solar yield and E_{fossil} is the annual fossil fuel consumption of the facility. **Table 4** illustrates the decrease in the solar heat fraction from scenario 2 to 3, where scenario 3 accounts for the current solar collector efficiencies and area utilization. We see that the reduction is three times for Tarragona and Mangualde, and five-seven times for Moosburg and Nettgau. Hence, the solar field area must be even larger for the FRIENDSHIP solutions to cover the heat demand of scenario 1 than what the previously calculated area demand indicates (i.e. 480%, 155%, 22% and 520%). On the other hand, additional thermal heat storage would be required to account for the natural fluctuations in the solar irradiation. This would increase the cost of retrofitting the FRIENDSHIP solutions compared to the current situation where the solar yield never exceeds the thermal demand, and thermal storage is unnecessary.

Although the introduction of the solar collector efficiencies in scenarios 3 and 4 reduces the solar heat fraction dramatically, the annual heat yield remains substantial. It is outside the scope of this report to do a detailed comparison of the FRIENDSHIP solutions with other renewable technologies. Instead, a rough calculation of the *energy* yield (in terms of electricity) from photovoltaic panels performed in the Global Solar Atlas is shown in the appendix. This estimates that the *thermal* yield of the FRIENDSHIP solutions today is the same or better (by more than two times) for Moosburg, Tarragona and Mangualde, respectively. It is only in Nettgau that the PV panels outperform the current FRIENDSHIP solutions by a factor of 0.75. Accounting for the improvement in the solar collector efficiencies with the target 2%, the FRIENDSHIP solutions will outperform the PV panels at all locations investigated herein. While this comparison suggests that the FRIENDSHIP solutions increases the renewable energy penetration at the facilities more than other green technologies, an important remark is that the comparison between thermal energy on one side and electricity on the other is challenging. The rough comparison shown herein may be unfairly biased towards solar heat and not provide enough detail to conclude on whether the FRIENDSHIP solution is the alternative for renewable energy generation the maximizes the renewable energy penetration at the facilities.

Table 4	**Solar heat fraction, f_{solar}, from** Eq. 4 **(%)**				**Annual CO2 reduction from** Eq. 6 **(tonnes)**			
Scenario	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Moosburg	23.40	3.61	0.75	0.86	8 709	1 345	278	319
Tarragona	65.00	41.92	14.68	16.98	4 595	2 964	1 038	1 201
Nettgau	82.39	36.02	5.34	7.31	19 020	8 316	1 232	1 687
Mangualde	597.68	15.77	5.53	6.32	-	-	-	-

Interestingly, we noticed two different trends in the decrease in the solar heat fraction from scenario 2 to 3: A three times decrease for Tarragona and Mangualde on one hand, and five-seven times decrease for Moosburg and Nettgau on the other. When the FRIENDSHIP project target efficiency improvement of 2% is accounted for in scenario 4, **Table 4** again shows two different trends: 1.15 time increase from scenario 3 to 4 for Moosburg, Tarragona and Mangualde, and 1.37 times increase for Nettgau. Since the area available for solar collectors is accounted for in scenarios 2, 3 and 4, the different trends must arise from the solar collector efficiencies or the DNI. Although the solar collector efficiencies are slightly different for the different facilities due to their different operating temperatures, the variations are small. Moreover, the operating temperatures do not change from scenario 3 to 4, indicating that the different trends in the increase in solar heat fraction from scenario 3 to 4 cannot be explained by the solar collector efficiencies. The DNI utilization increase, however, will vary for the different locations. In the following, we are therefore looking in more detail on the effect of the DNI on the solar heat yield.

5.1.2 Normalized solar heat yield and the effect of DNI

To isolate the effect of the DNI on the solar heat yield from that of the available area, we investigated the solar yield relative to the available area. **Figure 7** shows the solar yield divided by the available area for scenarios 3 (in blue) and 4 (in yellow) as a function of the total DNI. According to **Eq. 2**, the solar yield is linearly dependent on the DNI, assuming that the efficiency is independent of the DNI[a]. However, the trends both for scenarios 3 and 4 follow an exponential curve for the three first data points. This exponential trend may be explained by the exponential decay of the difference between the annual total DNI, DNI_0, and the annual threshold DNI, $DNI_{threshold}$. These differences in DNI are shown with square markers in **Figure 7** for scenarios 3 (in grey) and 4 (in orange). As delta DNI goes towards zero, the heat yield goes towards a linear dependence of DNI, in accordance with **Eq. 2**.

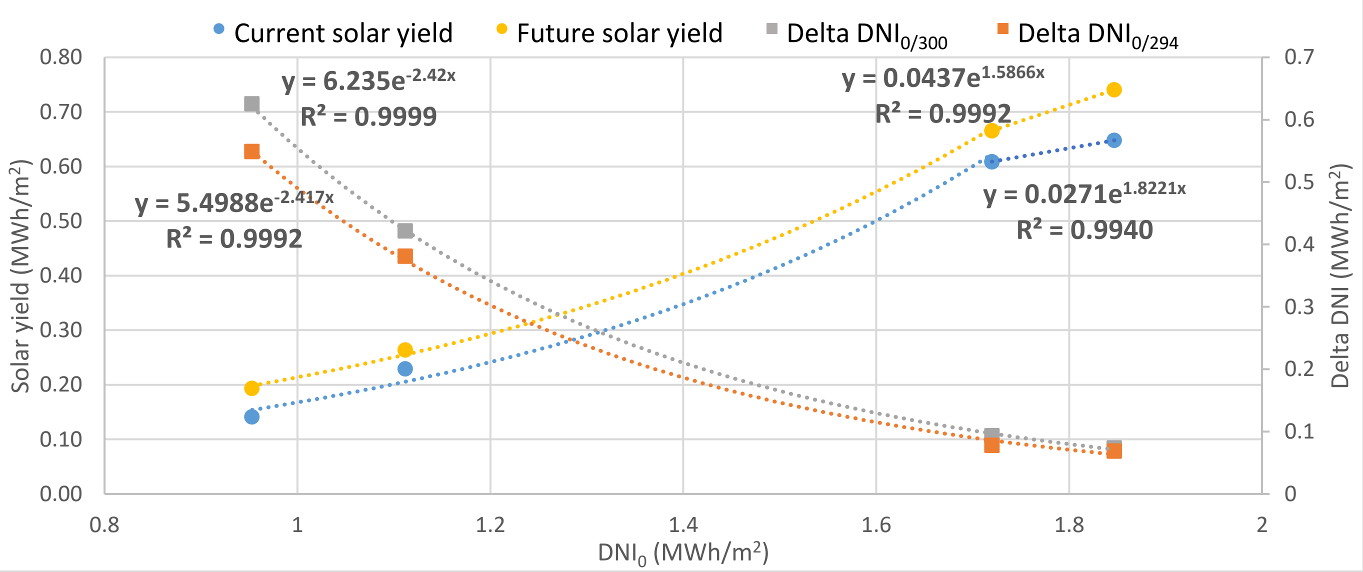

Figure 7. The solar yield weighted on the field area (circles) and the delta DNI (squares). The dotted lines are the regression lines. The equations for the regression lines are shown in bold above and below the solar yield (to the right) and the delta DNI (to the left).

There are two major implications of this exponential behaviour at lower DNIs. Firstly, the current heat yield at low DNIs is significantly affected by the solar collector power threshold. As a result, substantial heat yields may currently only be available at higher DNIs, especially when the area available to solar collectors is limited. Secondly, the trendlines of the future (in yellow) compared to the current (in blue) solar yield in **Figure 7**, shows that the 2 % improvement of the solar collector power threshold reduce the exponential behaviour of the future solar yield such that it approaches a linear dependency on the DNI. This is because the improvement makes more of the solar heat accessible to the collectors and reduces their down-time. Optimising the operation of the solar fields with respect to the solar power (*i.e.* decreasing the DNI threshold) is particularly beneficial in areas with lower DNI, and results in a relative increase in the heat yield, increasing the potential of FRIENDSHIP solutions at these DNIs.

5.1.3 Impact of HTHP and reduced solar field outlet temperature

In the previous assessments, we have excluded the high temperature heat pump (HTHP). Yet, combining the HTHP with the solar field is one of the novel features of the FRIENDSHIP solutions. This feature may be particularly attractive for the facilities in the northern part of Europe where the DNI is lower because it introduces the flexibility to reduce the outlet temperature of the solar field and use the HTHP to lift the temperature to the required process temperature. In the following, we therefore analyse the effect of reducing the solar field outlet temperature and covering the temperature gap to a process temperature of 200^{o}C with

---

[a] We see in **Eq. 1** that this assumption is not true, but the contribution to the overall efficiency from the second term in **Eq. 1** smaller than 0.009 %. We may therefore assume that the total thermal efficiency is independent of the DNI.

the HTHP for Moosburg in the north and Tarragona in the south. **Figure 8** shows the average power required for the solar field to heat water to the outlet temperature (solid line with circular markers), the power required for the HTHP to lift the temperature from the outlet to the process temperature at 200°C (solid line with square markers), and the solar field average power at the given outlet temperature (dotted line) for Moosburg (in blue) and Tarragona (in orange). The HTHP power required for the temperature lift is estimated according to **Eq. 3**, using the power from a PTC solar field averaged over the year. The average power, P_w, required to heat the process water flow to the solar field outlet temperature is estimated according to:

$$P_w(T_c) = \frac{E_w(T_c)}{t} = \left(H_g(T_c, p) - H_c(T_{con}, p)\right) \cdot \frac{m_w}{t},$$

Eq. 5

where E_w is the annual energy required to heat water to the specified solar field outlet temperature, T_c, t is the time (over a year), H_g is the enthalpy of the superheated steam at temperature T_c and pressure, p, and H_{con} is the enthalpy of the saturated liquid at temperature T_{con}, and m_w is the total, annual mass of water consumed in a facility. As specified in **Table 2**h, the saturated liquid temperature, T_{con}, is 10°C and 60°C and the pressure 16 bar and 13 bar for Moosburg and Tarragona, respectively.

The intersection between the solar field average power and the steam power (*i.e.* the dotted and the circular marked line) marks the average outlet temperature that the solar field can provide given the field's available area and the DNI$_a$ of the location. In Tarragona's case, the solar field is in fact able to heat the steam to 190°C. The combination with the HTHP can cover the temperature gap between 190°C and the required process temperature at 200°C at an average annual energy consumption of around 0.5 GWh. This reduces the energy consumed in steam production compared to the current consumption at 26 GWh, and may render the overall system carbon neutral, provided that the electricity supply is renewable. However, we notice that the calculations neither accounts for seasonal nor daily variations in the DNI. In reality, the solar field power will fluctuate with time, and may not be able to heat the steam to 190°C at all times, particularly at night and in winter (as illustrated in **Figure 3**), increasing the temperature gap covered by the HTHP. As seen in **Figure 8**, this will increase the HTHP energy consumption. Furthermore, it is uncertain how the HTHP will operate under variable supply temperature, potentially making auxiliary systems to heat the steam stream necessary. Nevertheless, we conclude that the integration potential of the FRIENDSHIP solutions at Tarragona will be larger with the inclusion of the HTHP compared to the case without the HTHP, and further increase the renewable energy penetration.

In contrast, the solar field average power and the steam power intersect at around 40°C in Moosburg's case, underlining the greater potential of the FRIENDSHIP solutions in areas with higher DNI$_a$, even when the HTHPs are included in the SHIP200 scheme. On the other hand, the lower solar field average power of Moosburg compared to Tarragona is not only caused by lower DNI$_a$, but also by lower area availability for the solar field. Assuming the same solar field area for Moosburg as for Tarragona shifts the intersect to 60°C. Accounting for the 2% target improvement in the solar collector performance, shifts the intersect with an additional 13 %, to around 70°C. It is still a question if the HTHP is capable of lifting the temperature from 70 to 200°C without the aid of auxiliary systems. If possible, however, it entails a seven-time reduction in the average annual energy consumed in producing steam compared to the current situation.

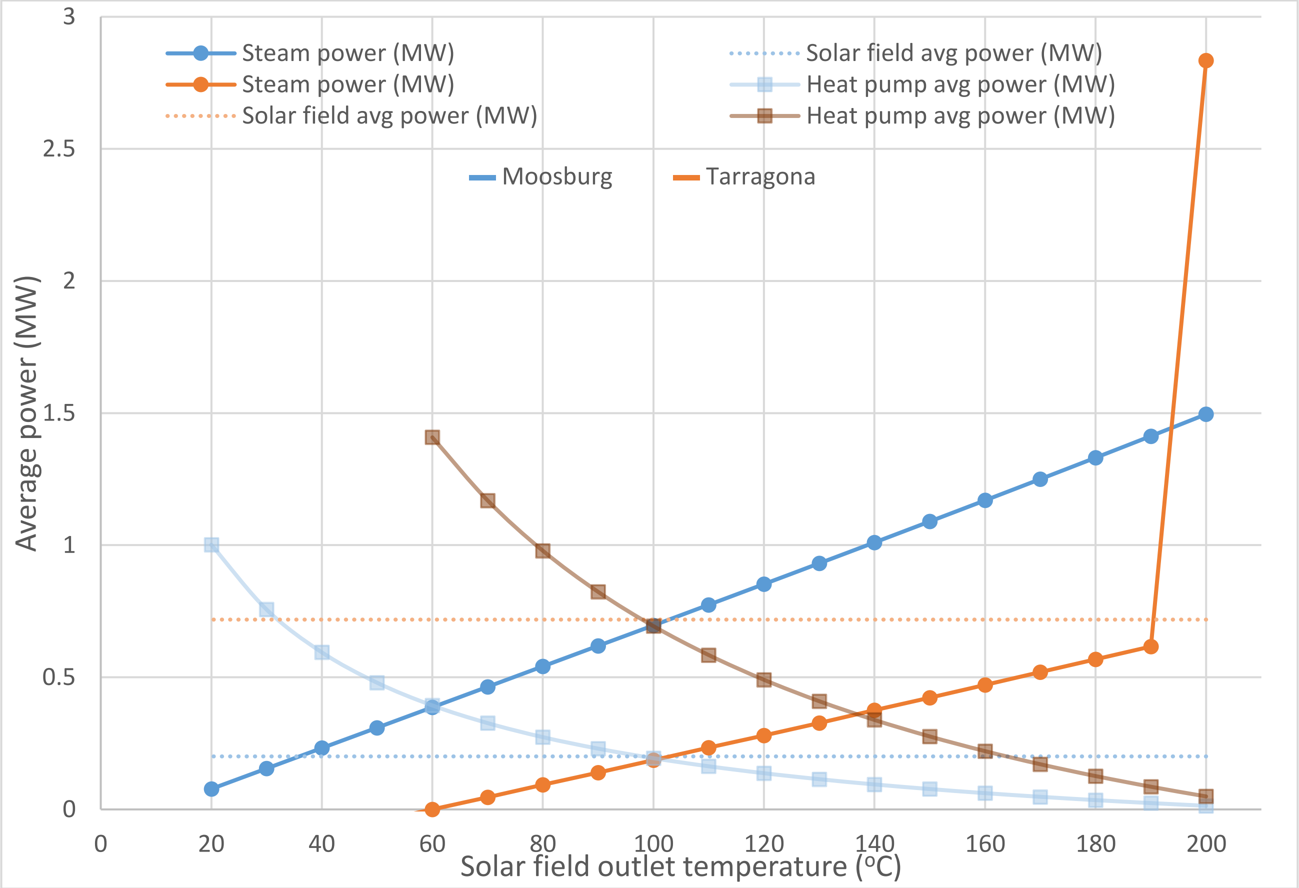

Figure 8. The average solar field, steam and heat pump power for Moosburg and Tarragona, calculated according to **Eq. 2** (but divided by the time over a year), **Eq. 5** and **Eq. 3**, respectively.

A final remark to **Figure 8** is that the overall energy consumption of the facility can be dramatically reduced if the processes can be optimized to use lower steam temperatures. For Tarragona, for example, reducing the process temperature from above 200°C to below 180°C involves a five-time reduction in the power consumption, which facilitates both higher energy efficiency and a more reliable energy delivery from the FRIENDSHIP solutions. Furthermore, we see that in areas with low DNI_a, such as in Moosburg, the solar heat yield is insufficient to reach high output temperatures from the solar field, and the HTHP may not be able to cover the large temperature gap to process temperatures up to 200°C. Yet, the solar collector-HTHP combination of the FRIENDSHIP solutions can be attractive for processes requiring lower temperatures than 200°C, but higher than the obtainable output temperature from the solar field.

5.2 FRIENDSHIP environmental mitigation potential

5.2.1 CO_2 Emission Reductions, LCA and corresponding cost saving

Replacing the fossil fuel currently consumed at the facilities with solar heat has a direct economic benefit for the facilities related to the lower energy price of solar heat compared to fossil fuel and the CO_2 taxation and the EU Taxonomy, which we will discuss more detailed in the next subchapter. For the local and global community, however, the benefits of the FRIENDSHIP solutions lie solely in the reduction of GHG emissions that the solar fields bring. Consequently, we have estimated the annual CO_2-reduction according to:

$$em_{reduced} = em_{annual} \cdot f_{solar},$$

Eq. 6

where $em_{reduced}$ is the annual reduction in CO_2 emissions corresponding to the solar heat fraction, f_{solar}, and em_{annual} is the annual, direct CO_2 emission from a facility. **Table 4** quantifies the annual CO_2 emission reduction for the four different scenarios. Since emissions from biomass fueled boilers do not fall under the reporting requirements of the EU ETS[12], Mangualde does not monitor its overall CO_2 emissions. Moreover, it is worth noting that for the other facilities, **Eq. 6** assumes that all the emissions come from fossil fuel consumption. This may not be true. For example in Clariant's chemical facilities, CO_2 can be a by-product from a chemical process, causing an overestimation of the annual reduction of CO_2 emissions resulting from the installation of solar fields. In Nettgau, the CO_2 emissions may include emissions from biomass. Since such emissions are not counted in the CO_2 balance that should be reported under the current Taxonomy, the reduction shown herein may be artificially high.

Table 4 shows that the potential for CO_2 reduction (i.e. reductions in scenarios 1 and 2) for Moosburg, Nettgau and Tarragona total to 12 000 - 32 000 tonnes CO_2 per year, corresponding to flying 400 persons 3 – 9 times around the Equator[17]. However, the emission reduction falls drastically in scenarios 3 and 4. Furthermore, these estimates do not account for the emissions related to the production and operation of the solar collectors. Rough life-cycle analyses (LCAs) have been performed by Absolicon and Industrial Solar for the PTCs and LFRs. The LCAs estimate that 125 kg CO_2eq/m^2 and 85.78 kg CO_2eq/m^2 is emitted for the two different solar collectors respectively. These estimates include the materials' production and assembly. Accounting for emissions during the operation of the LFRs, increases the LCA emissions to 185.8 kg CO_2eq/m^2 over the 25 years lifetime estimated for the LFRs. The total emission reduction for the three facilities over the 25 years that the solar collectors are assumed to operate is shown for all scenarios in **Table 5**.

Table 5	**Emission reduction over 25 years (tonnes CO_2eq)**			
Scenario	**1**	**2**	**3**	**4**
Moosburg	216 642	32 533	5 850	6 888
Tarragona	113 359	72 577	24 709	27 150
Nettgau	468 373	200 774	23 680	35 064

Although the emission reduction analyses herein disregard the impact of integrating the HTHPs in the SHIP200 scheme of Moosburg and Tarragona, we can estimate their impact by assuming that the SHIP200 scheme replaces all fossil fuel sources for steam production, resulting in emission reductions corresponding to scenario 1. Particularly for Tarragona, we can argue that this is the case, as discussed in section 5.1.3.

The economic benefits of the FRIENDSHIP solutions are connected to the CO_2 emission reductions obtained compared to a continued use of fossil fuels. In EU, the Emission Trading Scheme (ETS) sets a cap on the allowed GHG emissions from industries, resulting in a price tag on CO_2 emissions. The average cost of CO_2eq emitted was 80 EUR/tonne CO_2eq in 2021, but the price is expected to increase to 100 EUR/tonne CO_2eq over the next couple of years[18]. Additionally, the saved cost of reduced fossil fuel consumption increases the economic benefits of installing solar heat. Although it is inherently challenging to forecast fossil fuel price changes, the EU Commission performed impact assessments accompanying the "Fit-for-55"-plan under the Green Deal where, amongst others, the natural gas prices, which are relevant for this report, were predicted[19]. The assessments were, however, performed before the current escalation in the energy crisis, and may underestimate the price growth. Consequently, we have performed cost saving analyses based on multiple natural gas price forecasts: 1) the average natural gas price so far for 2022 at 98 EUR/MWh[20], and the forecasts from the Commission[19] for 2) 2025 at 16.4 EUR/MWh, 3) 2030 at 21.3 EUR/MWh, and 4) 2050 at 30.1 EUR/MWh. The revenue saved for Moosburg, Tarragona and Nettgau given the saved CO_2 tax and the saved cost for natural gas over the estimated life-time of 25 years for the solar collectors for scenarios 3 and 4 are shown in **Table 6**.

Table 6	**Estimated cost savings for Scenario 3 (million EUR)**				**Estimated cost savings for Scenario 4 (million EUR)**			
Natural gas price forecast	**2022**	**2025**	**2030**	**2050**	**2022**	**2025**	**2030**	**2050**
Moosburg	4.52	1.24	1.44	1.79	5.21	1.45	1.67	2.08

Tarragona	17.09	4.92	5.65	6.96	18.70	5.39	6.19	7.62
Nettgau	15.62	4.59	5.25	6.44	21.65	6.54	7.45	9.08

While it is perhaps unlikely that the natural gas prices remain at the current all-time-high for the next 25 years, the current European and global situations will affect the prices over the next few years, making the accumulated cost savings over the lifetime of the solar collectors larger than what the forecasts for 2025, 2030 and 2050 suggest. Consequently, it may be realistic to anticipate a cost saving of 1.44-5.21 million EUR, 5.65-18.70 million EUR and 5.25-21.65 million EUR over the subsequent 25 years (i.e., the lifetime of the solar collectors) after the installation of the FRIENDSHIP solutions. The upper limit also accounts for the increased cost savings accompanying an increase in the solar collector efficiency.

5.3 Overall FRIENDSHIP potential and potential in REII and SPIRE

The assessments of the integration and environmental mitigation potential of the FRIENDSHIP solutions show high potential for resources and energy-intensive industries (REII) with heat demand through steam production and/or thermal oil heating. In this report, the process temperatures range from 200 to 280^{o}C, covering the intended range for the FRIENDSHIP solutions. Even though the FRIENDSHIP solutions can be used for process temperatures lower than $180\text{-}200^{o}$C (*i.e.* the SHIP200 scheme), their main advantage compared to already commercially available solar heat solutions is for high process temperatures. An exception occurs in locations where the annual direct normal irradiation, DNI_a, is too low to reach temperatures above 100^{o}C. In that case, the unique combination of the solar field and the high temperature heat pump (HTHP) in the FRIENDSHIP project is attractive to reach process temperatures above the obtainable output temperature of the solar field.

Clariant's and Sonae's facilities, which are studied in this work, are distributed from north to south in Europe, displaying a range of DNI_zs. Our assessments show that the integration potential increases for facilities further south, with DNI_a above around 0.9 MWh/m^2, compared to facilities further north. Considering **Figure 1**, we see that the higher integration potential can be found in in Portugal, Spain, southern parts of France and Italy and along the coast of the Mediterranean Sea. Here, the FRIENDSHIP solutions can cover annual heat demands up to 30 GWh, as is the case for Tarragona, and CO_2 emissions substantially curbed or eliminated. To cover higher heat demands, our results show that the area available to the solar field may have to exceed what is typically available on roof tops.

Further north, the integration potential decrease. However, the FRIENDSHIP solutions are adaptable. The lack in DNI can to a large degree be compensated by increased area available to the solar field without substantially penalising the environmental mitigation potential, resulting in significant CO_2 emission reductions. Furthermore, our results show that improvements to the solar field efficiency, and particularly to the operational threshold, will benefit northern locations more than southern, and increase the integration potential. Thus, the FRIENDSHIP solutions become attractive in locations with low-medium DNI_a (*i.e.* in the range 0.5-0.9 MWh/m^2), opening the market for FRIENDSHIP solutions in counties with high industrial activity such as Germany.

In this report, we have focused on production facilities, and found that from a practical and legal point of view, the steam or thermal oil heating processes should occur on-site at the facility, and not be delivered by an external provider. However, the FRIENDSHIP solutions are equally attractive for the external provider of steam or hot thermal oil delivered to an industrial cluster. Depending on the size of the cluster, we may expect annual heat demands on the high end of, or exceeding, the heat demands of the facilities studied in this report. To cover the heat demand, high area availability for the solar fields, exceeding roof-top area, is a prerequisite.

6 Conclusions

In this report, we have investigated the integration and environmental mitigation potential of solar heat solutions developed in the EU Horizon 2020 project, FRIENDSHIP, for four different facilities located in Moosburg, Tarragona, Nettgau and Mangualde. The integration potential was assessed in terms of the share of solar heat, the solar heat fraction, possible in the energy portfolio of the facilities. Both the current state of the solutions and target 2 % improvements of the solar collector efficiencies were accounted for. Additionally, the impact of integrating high temperature heat pumps (HTHPs) with the solar field to reach process temperatures up to 200°C, was estimated for the two relevant facilities in Moosburg and Tarragona. Since the HTHP which is developed in the project is not validated yet, only a simplified model for the HTHP is used in the estimation. Moreover, the HTHP is not considered explicitly in the environmental mitigation potential, which was evaluated as the CO_2 emission reduction corresponding to the solar heat fraction.

The integration potential assessments showed that the highest solar heat fractions were obtained for the facilities located in areas with high annual direct normal irradiation (DNI_a) and/or large amount of area available for the solar field. In areas with medium to low DNI_a, meaning lower than approximately 0.9 MWh/m^2 annually, the increase in solar field area counteracts the effect of low irradiation. Our results show that due to the low carbon footprint of the solar collector production, such an increase in solar field area will not penalise the environmental mitigation potential significantly. Thus, available area exceeding what is typically accessible at roof-tops is increasingly important in the northern parts of Europe.

In all facilities herein, steam production and/or thermal oil heating were identified as processes where the fossil energy source could be replaced by FRIENDSHIP solutions. The magnitude of the annual heat demand ranged from 25 to 90 GWh, out of which less than 50 % could be replaced by solar heat even when the efficiency of the solar field was set to 100 %. Increasing the area available to the solar field is the easiest way to increase the solar fraction. Our results indicate that the FRIENDSHIP solutions have higher heat yield than standard photovoltaic solutions. Although this comparison is simplified to the extent where it can be challenging to conclude that the FRIENDSHIP solutions perform better than other renewable technologies for the applications in resources and energy-intensive industries (REII), we also found that the environmental mitigation potential is not penalised significantly by an increase in the solar field area. Consequently, adjusting the solar field area to meet the heat demand of the facility can be justified from an environmental point of view.

In the assessments above, the integration of HTHPs were not considered. If the HTHPs are integrated with the solar field in Tarragona, the yield of the complete system can cover the entire heat demand of the facility. The input energy to the HTHP is uncertain at this point since the HTHPs are not validated yet, however, an estimation indicates an annual electricity consumption of 0.5 GWh, far below the current annual heat consumption at 26 GWh. In Moosburg, a similar assessment showed that the low heat yield of the solar field, caused by both low DNI_a and low solar field area, leaves a temperature gap of 160°C for the HTHP to lift to reach process temperatures at 200°C. Although the estimated annual electric energy required for this lift is below the current heat consumption, the HTHP may not be capable of such a lift. Nevertheless, the HTHP integration in the solar heat scheme is attractive in the northern parts of Europe because it can be used to reach medium process temperatures in the range around 140°C to 200°C, using smaller solar field areas.

Additionally, the facilities in the northern parts of Europe are found to benefit more from improvements to the solar field efficiencies than the facilities in the south. The target improvement of the FRIENDSHIP project at 2 % is found to give almost 40 % increase in the performance of the northernmost facility with the lowest DNI. Over the lifetime of the solar field, this corresponds to a CO_2 emission reduction of 35 kilo tonnes. Due to lower area availability at the other facilities, the cumulated CO_2 reduction of the lift-time of the solar field is lower. Still, the estimated cost savings accounting for the CO_2 taxation in the EU as well as different scenarios in the natural gas price development, are 1.2-5.2, 4.6-21.6 and 4.9-18.7 million EUR for Moosburg, Nettgau and Tarragona, respectively.

Finally, we have identified a set of general features among the facilities investigated in the presented work, aiming to guide the deployment of the FRIENDSHIP solutions in REII outside the project's consortium. In general, facilities and industries relevant for deployment of the FRIENDSHIP solutions have a significant heat demand compared to the remaining energy consumption, the heat is used to produce steam or hot thermal oil, and the current energy source is fossil fuel. Since the solar heat yield heavily depends on the area available for solar collectors and the location of the facility, which determines the DNI_a, the attainable process temperatures and heat yields will vary from facility to facility. Generally, the solar heat yield can only cover annual heat demands up to a few GWh for process temperatures between 200 and 300^{o}C unless solar field areas beyond roof-tops are available.

For process temperatures up to 200^{o}C and in locations with medium to high DNI_a, meaning above 0.9 MWh/m^2, roof-top solar collector area can be sufficient to cover heat demands up to 30-50 GWh, due to the combination of the solar field and the HTHPs. Some electric energy input to the heat pump is still necessary, but the overall energy demand is dramatically reduced compared to the original case with fossil fueled boilers. Nevertheless, the HTHP energy consumption is reduced for increased solar field area, and available area beyond roof-tops is generally beneficial from both an environmental and economic perspective.

In locations with low to medium DNI_a, meaning from 0.5 to 0.9 MWh/m^2, it is unlikely that the current technology can reach process temperatures as high as 200^{o}C, even with the help of the HTHP, unless the area used for solar collectors is increased dramatically beyond roof-top availability. Nonetheless, the FRIENDSHIP solutions with the HTHP integrated can be attractive for industries with process temperature requirements lower than 160^{o}C since these can be achieved with lower area usage than with standard solar heat collectors.

Lastly, we notice that improvements to the solar collector efficiencies will shift the requirements to the DNI_a to lower values. Already achieving the 2 % improvement target of the FRIENDSHIP projects enables lower area usage, higher obtainable process temperatures and higher renewable energy penetration in facilities located all the way from Germany in the north going south in Europe.

7 Degree of Progress

Degree of fulfilment of the task activities respect of what reported in the DoA is 100%.

8 Dissemination Level

This Deliverable is public.

9 References

1. Ge, M., Friedrich, J. & Vigna, L. 4 Charts Explain Greenhouse Gas Emissions by Countries and Sectors. *World Resources Institute* https://www.wri.org/insights/4-charts-explain-greenhouse-gas-emissions-countries-and-sectors (2020).
2. Sharma, A. K., Sharma, C., Mullick, S. C. & Kandpal, T. C. Potential of solar industrial process heating in dairy industry in India and consequent carbon mitigation. *Journal of Cleaner Production* **140**, 714–724 (2017).
3. Naegler, T., Simon, S., Klein, M. & Gils, H. C. Quantification of the European industrial heat demand by branch and temperature level. *International Journal of Energy Research* **39**, 2019–2030 (2015).
4. Kumar, L., Hasanuzzaman, M. & Rahim, N. A. Global advancement of solar thermal energy technologies for industrial process heat and its future prospects: A review. *Energy Conversion and Management* **195**, 885–908 (2019).
5. Lauterbach, C., Schmitt, B., Jordan, U. & Vajen, K. The potential of solar heat for industrial processes in Germany. *Renewable and Sustainable Energy Reviews* **16**, 5121–5130 (2012).
6. Sharma, A. K., Sharma, C., Mullick, S. C. & Kandpal, T. C. Solar industrial process heating: A review. *Renewable and Sustainable Energy Reviews* **78**, 124–137 (2017).
7. Weiss, W. & Spörk-Dür, M. *Solar Heat Worldwide, Global Market Development and Trends in 2018*. https://www.iea-shc.org/Data/Sites/1/publications/Solar-Heat-Worldwide-2019.pdf (2019).
8. Industrial Solar. Fresnel collector LF-11. https://www.industrial-solar.de/en/technologies/fresnel-collector/ (2020).
9. Absolicon. Data sheet T160 Solar Collector. *Absolicon* Preprint at https://www.absolicon.com/wp-content/uploads/2020/04/SALMARENG004_18_T160-Collector-Data-Sheet_EN_Web.pdf.
10. Ahlgren, B. *et al.* A simplified model for linear correlation between annual yield and DNI for parabolic trough collectors. *Energy Conversion and Management* **174**, 295–308 (2018).
11. Solargis. Global Solar Atlas 2.0. A free web-based application developed and operated by the company Solargis s.r.o. on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP). https://globalsolaratlas.info/.
12. Andersen, S. P., Allen, B. & Domingo, C. *Biomass in the EU Green Deal: Towards consensus on the use of biomass for EU bioenergy*. https://ieep.eu/uploads/articles/attachments/a14e272d-c8a7-48ab-89bc-31141693c4f6/Biomass%20in%20the%20EU%20Green%20Deal.pdf?v=63804370211 (2021).
13. Cefic. 2022 Facts And Figures Of The European Chemical Industry. *Cefic* https://cefic.org/a-pillar-of-the-european-economy/facts-and-figures-of-the-european-chemical-industry/ (2022).
14. Statistica. Revenue of the leading chemical companies in Europe in 2021. *Statistica 2022* https://www.statista.com/statistics/443135/top-chemical-companies-in-europe-by-turnover/ (2022).
15. Cefic. Landscape Of The European Chemical Industry. *Cefic* https://cefic.org/a-pillar-of-the-european-economy/landscape-of-the-european-chemical-industry/ (2022).
16. Cepi. Industry Statistics. *Cepi* https://www.cepi.org/statistics/ (2022).
17. Campbell, I. Aviation. *Carbon Independent* https://www.carbonindependent.org/22.html (2007).
18. IETA & PwC. *GHG Market Sentiment Survey 2022*. https://www.ieta.org/resources/Documents/IETA%20GHG%20Market%20Sentiment%20Survey%20Report%202022.pdf (2022).
19. European Commission, D.-G. for C. A. *Impact Assessment - Stepping up Europe's 2030 climate ambition*. https://eur-lex.europa.eu/resource.html?uri=cellar:749e04bb-f8c5-11ea-991b-01aa75ed71a1.0001.02/DOC_2&format=PDF (2020).
20. Global Witness. The EU's €250 billion gas gamble. *Global Witness* https://www.globalwitness.org/en/campaigns/fossil-gas/the-eus-250-billion-gas-gamble/ (2022).

10 Appendix

10.1 Photovoltaic yield estimation

The rough estimation of the photovoltaic yield was found using the Global Solar Atlas[11], and assuming that 400 W solar panels could be used in all locations. The solar panel gross size was 2.11 m^2, giving an installed capacity of 1.33, 1.86, 7.26 and 0.95 MW at Moosburg, Tarragona, Nettgau and Mangualde, respectively. The resulting annual photovoltaic output energies are 1516, 2909, 7347 and 1461 MWh/year for Moosburg, Tarragona, Nettgau and Mangualde.

10.2 Comparison between the photovoltaic and solar heat yield

The comparison between the photovoltaic yield and the solar heat yield is displayed in **Table 7**.

Table 7. Comparison between the photovoltaic yield obtained from the Global Solar Atlas[11] and the FRIENDSHIP heat yield with the current efficiencies and with the 2 % efficiency improvement

	Photovoltaic yield (MWh/year)	Solar heat yield (MWh/year)	Solar heat yield with 2 % efficiency improvement (MWh/year)
Moosburg	1 516	1 606	1 847
Tarragona	2 909	5 967	6 522
Nettgau	7 347	5 407	7 405
Mangualde	1 461	3 239	3 703