SHIP2FAIR Pre-Feasibility Replication studies

Deliverable 8.4
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SHIP2FAIR - Solar Heat for Industrial Process towards Food and Agro Industries commitment in Renewables

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ABREVIATIONS

ETC: Evacuated Tube Collector
FPC: Flat Plate Collector
GHG: Greenhouse Gas
HVFP: High-Vacuum Flat Plate Collectors
LCPC: Linear Compound Parabolic Collectors
LFR: Linear Fresnel Reflector
PTC: Parabolic Troughs Collectors

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RINA-C: RINA Consulting S.p.A.
CEA: Commissariat à l'énergie atomique et aux énergies alternatives
ISMB: Istituto Superiore Mario Boella sulle tecnologie dell'informazione e delle telecomunicazioni
SOLID: S.O.L.I.D. Gesellschaft für Solarinstallation und Design mbh
TVP: TVP Solar
ISG: Industrial Solar GmbH
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RAR: RAR – Refinarias de Açúcar Reunidas S.A.
ABC: ABC Industrie SAS
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PUBLISHABLE SUMMARY

This report includes the results of SHIP2FAIR T8.4, with reference to 10 replication studies carried out with the SHIP2FAIR Replication Tool. The aim of the studies has been to demonstrate the technical and financial feasibility, the maturity and affordability of solar thermal technologies for implementation in industrial processes.

The replication studies refer to 10 sites in 6 different countries (Italy, Spain, France, Slovenia, Jordan, India), and to 8 different industrial sectors (textile, chemical, wastewater treatment, dairy, meat processing, brewery, food, and research laboratory). It is highlighted that the current public deliverable only presents the key results of the replication studies in anonymized form, in order to protect sensitive information regarding the companies; the complete version of the studies has been delivered to the European Commission separately from the main report.

The execution of the replication studies has allowed drawing general conclusions in addition to the site-specific results. Specifically, it has been shown that solar thermal technologies have a good potential for implementation in all industrial sectors characterized by a significant thermal energy demand, provided that site-specific prerequisites are met, such as solar resource availability (varying with latitude and local conditions as orientation/slope/obstacles) and of space availability for the installation of solar thermal plants. The most suitable technology based on energy/environmental and financial parameters can always be done: the main barrier is constituted to the still low financial profitability for these solutions, which however could increase significantly in case public incentives are available to support these technologies and in case the market price of fuels increase, like following 2022 geopolitical situation. Based on the studies carried out, the Levelized Cost of Heat varies between 17 and 109 €/MWh and the payback time between 3 and 20 years. While HVFP collectors showed the best performance and economical KPIs for process temperatures below 100°C and water as heat transfer fluid, Fresnel technology resulted as best suitable technology for temperatures above 100°C with water or steam as heat transfer fluid.

This report is complemented by a special evaluation of a representative sample of the Spanish agri-food industry - represented by one of the partners: SPANISH CO-OPS - in order to make a diagnosis of the current penetration of solar thermal and the intentions for the near future with regard to this technology.

TABLE OF CONTENTS

1 INTRODUCTION

This document constitutes D8.4 of the SHIP2FAIR Project and focuses on replication studies carried out with the SHIP2FAIR Replication Tool, aimed at showing the potential replicability and the techno-economic viability, maturity and affordability of solar heat technology for industrial process.

The replication studies have been realized by all partners involved in the Task activities for 10 sites, belonging to 8 different sectors (textile, chemical, wastewater treatment, dairy, meat processing, brewery, food, laboratory) in 6 different Countries (Italy, Spain, France, Slovenia, Jordan, India).

Due to the confidential nature of the information on which replication studies are based (company location, layout, process flow diagram, energy consumption and production values), the present public deliverable only presents the main outcomes of the replication studies in anonymized form. The complete documents with the replication studies are included as confidential Appendices to the present report, which are delivered to the European Commission separately from this core part of the document.

The document is articulated as follows:

- Chapter 1 constitutes the introduction to the present report;
- Chapter 2 presents the methodology adopted for the replication studies;
- Chapter 3 summarizes the main results of the replication studies;
- Chapter 4 is focused on the analysis and discussion of results of replication studies to extrapolate lessons learnt;
- Chapter 5 draws the conclusions of the analysis.

In addition to the pre-feasibility studies, a prospective study was carried out on a representative sample of the Spanish agri-food industry, as this is one of the sectors that can use it to develop its processes. The conclusions are presented in section 6 of this report.

2 METHODOLOGY

The present section focuses on the methodology applied for the execution of the replication studies, in terms of tool used (the SHIP2FAIR tool), data required and data sources used. The same section is reported in each replication study document in order to provide companies with an overview of the methodology applied for the analysis.

2.1 The SHIP2FAIR Tool

One of the main objectives of SHIP2FAIR project is to develop a software tool able to evaluate the techno-economic potential of such solution starting from local solar potential and current process heat demand, and to provide recommendations for the most suitable solution of integration.

Figure 1 shows the general scheme of the Replication Tool: this software tool uses as inputs the data from the solar resource and the industrial process thermal demands and temperatures of process in order to provide simulation results obtained from the baseline algorithm and the integration algorithm.

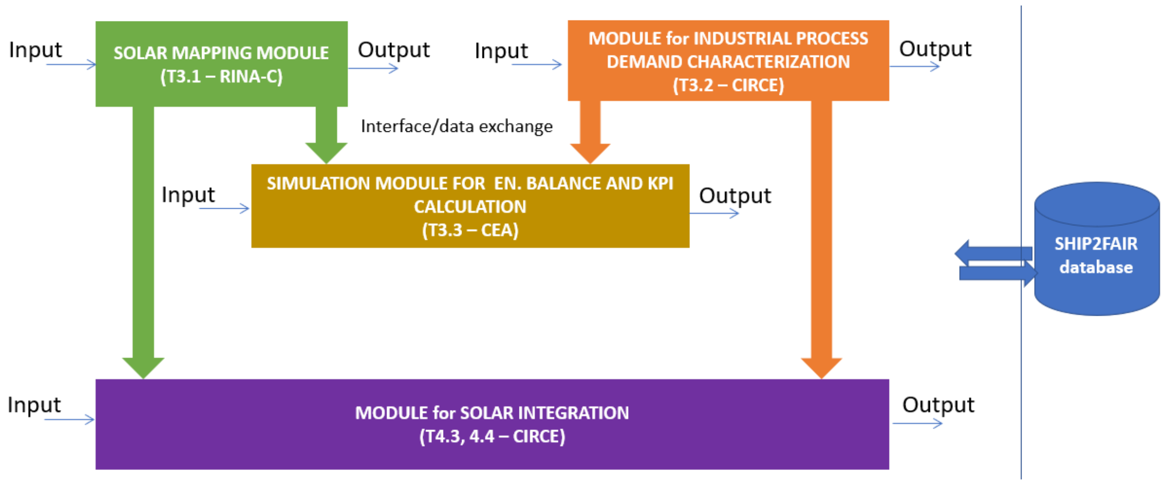

Figure 1: General Scheme of SHIP2FAIR Replication Tool

As shown in the Figure, the Replication Tool is based on four modules:

- Solar Mapping Module, which estimates the solar thermal theoretical potential according to local conditions in terms of solar irradiance and usable area for installing solar thermal collectors; it provides to the Simulation Module the following outputs on an hourly basis: Global Horizontal Irradiance (GHI); Global in-plane irradiance; Sun's position (azimuth and elevation); wind speed; ambient temperature; long-wave down welling infrared radiation;
- Industrial Process Demand Characterization Module, which assesses the heat demand of the industrial processes selected by the user according to simplified models, based on inputs from users regarding the energy sources consumption, the equipment involved and the operating schedule of the different processes; its output is a hourly basis thermal demand for a whole year;
- Simulation Module, which assesses the annual solar heat delivered by the user-defined solar plant (solar field and storage) to the process, quantifying different Key Performance Indicators to support technical, environmental and economic considerations on the different technologies aimed at identifying the optimal solution;

- Solar integration module, which identifies the best solar integration point within the different process in the industry, solving the critical issue related to dynamic integration of solar energy into an industrial process; it also carries out an exergy-based assessment of the optimal configuration.

2.2 Data Required (from Replication Cases/ Industrial Sites)

The following Tables present a list of inputs needed for the use of the SHIP2FAIR replication tool, with indication of notation, if applicable, and comments. In many cases, default values are available, which anyhow can be personalized by the user.

Specifically, Table 0.1 lists the inputs of the General tab, Table 0.2 the inputs of the solar mapping module, Table 0.3 those of the thermal demand characterization module, Table 0.4 the data needed for the simulation module and Table 0.5 those for the integration module.

Table 0.1: General User's inputs list

Name	Notation	Comment
User last name, user first name, user email, password		To register and login. Asked in popups before the "General Information" section.
Contact information (contact name, email, phone).		
Company name, city, country		
Product information (sector, name, year of study, year of production, total yearly production)		Sector selected by predefined list of sectors.

Table 0.2: Solar Mapping Module User's inputs list

Name	Notation	Comment
Latitude of the industrial site		
Longitude of the industrial site		
Panel Slope		Optional, can be optimized by the system.
Panel Orientation		Optional, can be optimized by the system.
Reference period (start year)		
Reference period (start year)		
Timezone		
Area for solar field installation		
Type of installation		Roof/ground.

Name	Notation	Comment
Roof typology		• Flat Roof • Sloped Roof (2 pitches): E-W oriented • Sloped Roof (2 pitches): N-S; NE-SW; NW-SE oriented • Shed Roof
Roof slope		
Corrective factor 1		Inclination & Obstacles
Corrective factor 2		Shading
Corrective factor 3		Maintenance Allowance

Table 0.3: Thermal Demand Characterization Module User's inputs list

Name	Notation	Comment
Energy sources		Electricity, Natural Gas, Propane, Butane, Diesel, Heavy Fuel Oil, Biomass High HV, Biomass Low HV
Monthly Energy Consumption		For each energy sources inserted.
Equipment name (ID), equipment type, number of simultaneous units		Equipment type: • Boiler - Condensing, • Boiler - Low Temp. • Boiler – Conventional • Chiller – Compression • Chiller - High Eff. • CHP – TG • CHP – TV. • CHP – Motor
Energy Sources Consumption Distribution (%). Power information (Nominal Power, Load factor, Efficiency). Processes that are supplied by the current equipment.		For each equipment. Mark the processes that are supplied by the current equipment. If known, please include the % of the nominal power dedicated to each process, otherwise the default value will be 100%. Note that in case the processes are not working simultaneously the % should be 100%.
Thermal use (heating/cooling), working fluid (Water, Steam), Op. temperature, Pressure (for Steam), thermal process dependency on external temperature (no dependence, air dependence, water dependence),		For each combination equipment-process. Select the daily profile that better fits this process (Constant Load, Morning Load, Afternoon Load, Full day Load, Batch Load).

Name	Notation	Comment
Definition of hourly, weekly and daily consumption profiles.		Select the typical daily profile for each day for the week, and assign a loading factor in percentage. Assign a loading factor in percentage for each week of the year.

Table 0.4: Simulation Module User's inputs list

Name	Notation	Comment
Number of cases	none	Number of cases to be compared. Between cases, solar collector technology, performance coefficients, solar field layout (ground orientation and slope, absolute collector orientation and slope, land occupation factor), collectors and land costs, lifetime, annual solar collector performance degradation rate, solar plant electricity consumptioncan be different (actually all inputs contained in a case definition).
Cases names	none	This is the names of the curves displayed to the user
Solar collector technology	none	7 types: • Flat Solar Collectors (FPC) • High-Vacuum Flat Plate (HVFP) • Evacuated Tubes Collectors (ETC) • Linear Fresnel Collector (LFR) • Linear Compound Parabolic Collectors (LCPC) • Parabolic Troughs Collectors (PTC) • Evacuated Tubes Collectors (ETC) – Viessmann Vitosol type
Absolute collector orientation	α_{col}	**DEFAULT VALUE comes from SMM**
Absolute collector slope	b_{col}	Useless for PTC and Fresnel: b_{col} =b_{gr} (no slope of this collector technology relatively to the ground/roof) **DEFAULT VALUE comes from SMM otherwise**
Ground/roof orientation.	α_{gr}	By default, the ground/rooftop is facing south **DEFAULT VALUE PROVIDED**
Ground/roof slope	b_{gr}	**DEFAULT VALUE comes from SMM**

Name	Notation	Comment
Collector slope, relative to the ground/roof, defined from 0 to 90°	b_{col_gr}	only for viessman types default value is 0 as the interest of the internal rotation is to have no tilt of the entire collector. **DEFAULT VALUE PROVIDED**
Collector axis orientation on the aperture plane	α_{col_in}	only for tubes, CPC, Viessmann. Can be only 0 or 90° **DEFAULT VALUE PROVIDED**
Ratio collector aperture / surface : Land occupation factor (relative to the collector)	$LOF_{\_col}$	Only for viessman type collectors, useless otherwise. **DEFAULT VALUE PROVIDED**
Number of tubes	N_{tubes_col}	
Ratio collector surface / maximum surface available for solar field installation : : Land occupation factor (relative to the solar field)	$LOF_{\_SF}$	This input defines the entire collector surface knowing S_{gr} from SMM. **DEFAULT VALUE PROVIDED**
Number of collector rows	N_{rows_SF}	Useless for Fresnel. **DEFAULT VALUE PROVIDED**
Optical efficiency	η_0	Relative to the gross collector area, except for fresnel: relative to mirror area. **DEFAULT VALUE PROVIDED**
Zero heat loss coefficient	c_1	**DEFAULT VALUE PROVIDED**
Temperature effect on c_1 coefficient	c_2	**DEFAULT VALUE PROVIDED**
Wind effect on c_1 coefficient	c_3	**DEFAULT VALUE PROVIDED** This input is optional
Sky temperature effect on c_1 coefficient	c_4	**DEFAULT VALUE PROVIDED** This input is optional
Wind effect on $\eta_0$coefficient	c_6	**DEFAULT VALUE PROVIDED** This input is optional
Incident Angle Modifier for diffuse light	IAMd	Requested for flat, tubes, CPC, viessman. Useless otherwise. **DEFAULT VALUE PROVIDED**

Name	Notation	Comment
Incident angle	θ	**DEFAULT VALUE PROVIDED**
Transversal Incident Angle Modifier	IAM T	2 IAM requested for tubes, Fresnel, CPC, Viessman. **DEFAULT VALUE PROVIDED** It is supposed that the size of the IAM T array is the same as the IAM L array
Longitudinal Incident Angle Modifier	IAM L	
Incident Angle Modifier	IAM	1 IAM for flat or PTC. **DEFAULT VALUE PROVIDED**
Temperature difference at the process level	$\Delta T_{process}$	Assumed to be equal to the nominal temperature difference in the solar field. **DEFAULT VALUE PROVIDED**
Temperature difference between the mean process temperature and the mean solar field temperature	$\Delta T_{process-SF}$	Positive (process – solar field) **DEFAULT VALUE PROVIDED**
Storage capacity max	$C_{storage\_max}$	**DEFAULT VALUE PROVIDED**
Number of storage capacity cases	none	**DEFAULT VALUE PROVIDED**
Storage type	none	2 cases: Case 1: Constant efficicency Case 2: Thermocline Thermocline by default
Storage efficiency	$\eta_{storage\_efficiency}$	Requested if storage type =1 **DEFAULT VALUE PROVIDED**
Storage fluid density	$\rho_{storage}$	**DEFAULT VALUE PROVIDED**
Storage fluid mass heat capacity	$c_{p\_storage}$	**DEFAULT VALUE PROVIDED**
Collector fluid mass heat capacity	$c_{p\_solar\_field}$	**DEFAULT VALUE PROVIDED**
Storage thermal losses coefficient	$U_{storage}$	Heat loss coefficient of the storage tank, between the fluid and the ambient Requested if storage type =2. **DEFAULT VALUE PROVIDED**
Solar plant electricity consumption	S_{p_elec}	Relative to the gross collector area, except for fresnel: relative to mirror area. **DEFAULT VALUE PROVIDED**

Name	Notation	Comment
Electrical efficiency	$\eta_{él}$	**DEFAULT VALUE PROVIDED**
Boiler efficiency	η_{boiler}	**DEFAULT VALUE PROVIDED**
traditional energy cost	FE_{cost}	**DEFAULT VALUE PROVIDED**
annual traditional energy cost increase rate	El_{cost}	**DEFAULT VALUE PROVIDED**
lifetime	$lifetime$	**DEFAULT VALUE PROVIDED**
CAPEX	$CAPEX$	Relative to the gross collector area, except for fresnel: relative to mirror area. **DEFAULT VALUE PROVIDED**
CAPEX_TES	$CAPEX\_TES$	**DEFAULT VALUE PROVIDED**
OPEX	$OPEX$	**DEFAULT VALUE PROVIDED**
OPEX_TES	$OPEX\_TES$	**DEFAULT VALUE PROVIDED**
CAPEX_land	$CAPEX\_land$	**DEFAULT VALUE PROVIDED**
Inflation rate	$Inflation$	**DEFAULT VALUE PROVIDED**
Degradation rate	$Degradation$	**DEFAULT VALUE PROVIDED**
Weighted Average Cost of Capital	$WACC$	**DEFAULT VALUE PROVIDED**
CO_2 emissions from light fuel oil	$CO2_{light\_fuel\_oil}$	**DEFAULT VALUE PROVIDED**
CO_2 emissions from heavy fuel oil	$CO2_{heavy\_fuel\_oil}$	**DEFAULT VALUE PROVIDED**
CO_2 emissions from liquefied petrol gas	$CO2_{liquefied\_petrol\_gas}$	**DEFAULT VALUE PROVIDED**
CO_2 emissions from natural gas	$CO2_{natural\_gas}$	**DEFAULT VALUE PROVIDED**
CO_2 emissions from coal	$CO2_{coal}$	**DEFAULT VALUE PROVIDED**

Table 0.5: Integration Module User's inputs list

Name	Notation	Comment
Type of optimization		Energy, Exergy, Energy & Exergy

Name	**Notation**	**Comment**
Working fluid		• Hot water (< 100°C) • Steam (100-200 °C) • High T how water (> 100 °C)

3 PRE-FEASIBILITY STUDIES

This section summarizes the main results of each replication study carried out in the Task. As anticipated in the Introduction, the results are presented in anonymized form to guarantee the confidentiality of the information used to carry out the study.

3.1 Case Study 1 – Textile, Italy

Subject of the study is a textile plant in Italy, carrying out washing and dyeing of wool, cotton and linen fabrics produced in other industries.

The plant uses energy in form of natural gas and electricity, which account for 87% (1,847,000 Nm^3/y, i.e. 18,175 MWh/y) and 13% (2,650 MWh/y) of the total final energy use, respectively. The greenhouse gases emissions of the plant are estimated at about 4,767 tCO_2e/year, 73% of which due to direct natural gas combustion and 27% of which indirectly due to electricity purchase from the grid.

Based on estimations carried out in the energy and resource efficiency audit of the plant, 32% of the steam produced by the boilers is used in the dyeing department (for processes carried out at 70°C), 40% in the finishing department (for processes in average at 60°C) and 28% in the washing department (for processes in average at 50°C).

The trend of hourly and monthly heat demand modelled with the SHIP2FAIR tool is presented respectively in Figure 2 and Figure 3.

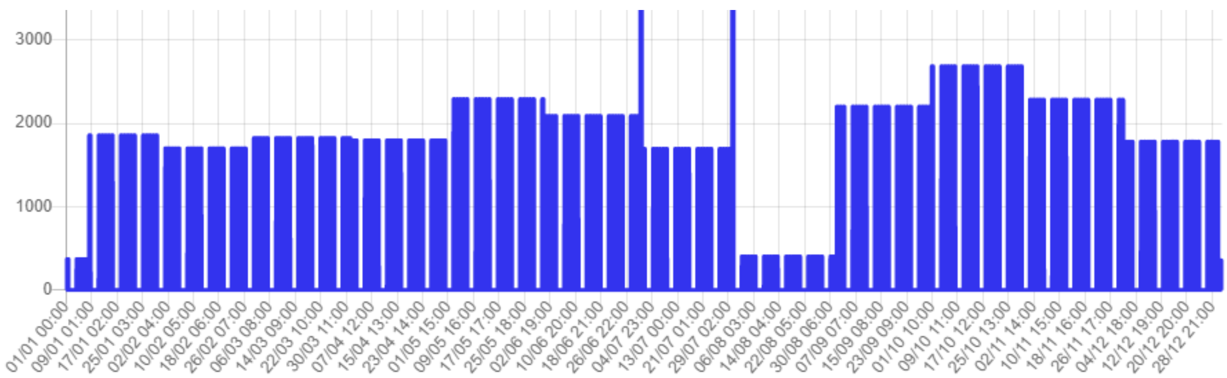

Figure 2: Modeling of Total Hourly Heat Demand

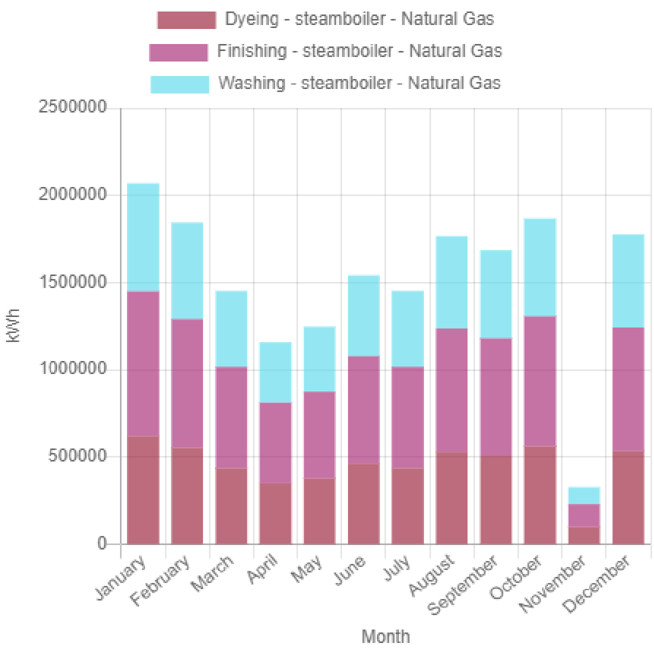

Figure 3: Modeling of Monthly Heat Demand and Breakdown among Processes

The roof of the industrial site is constituted by a series of two-pitched sloped roofs, oriented E-W and with inclination of 20°. No significant obstacles and sources of shading are present, neither significant space is required for other installations. Based on the preliminary information gathered, all the roof area is suitable for the installation of solar panels.

The monthly profiles of direct normal and global solar irradiance at the site are presented in Figure 4.

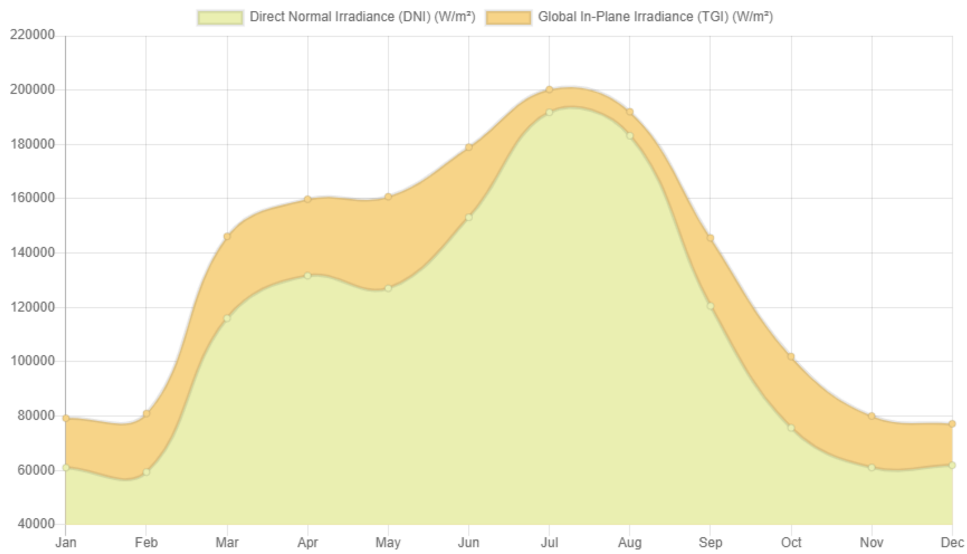

Figure 4: Direct Normal and Global In-Plane Solar Irradiance Monthly Profiles

The target plant requires for its processes heat in form of hot water at 50-70°C. Based on this range of operational temperatures, in line with the matching carried out in SHIP2FAIR D2.1, three technologies are identified as potentially most appropriate and are briefly described below:

- flat plate collectors (FPC);
- evacuated tube collectors (ETC);
- linear Fresnel reflectors (LFR) with single-axis tracker.

Based on the algorithms implemented in the SHIP2FAIR replication tool the following maximum areas were considered for the different technologies of solar collectors:

- 827 m^2 for FPC;
- 1,193 m^2 for ETC;
- 1,118 m^2 for LFR.

The potential monthly thermal energy production of those solutions are compared with the monthly heating demand of the site in the chart in Figure 5.

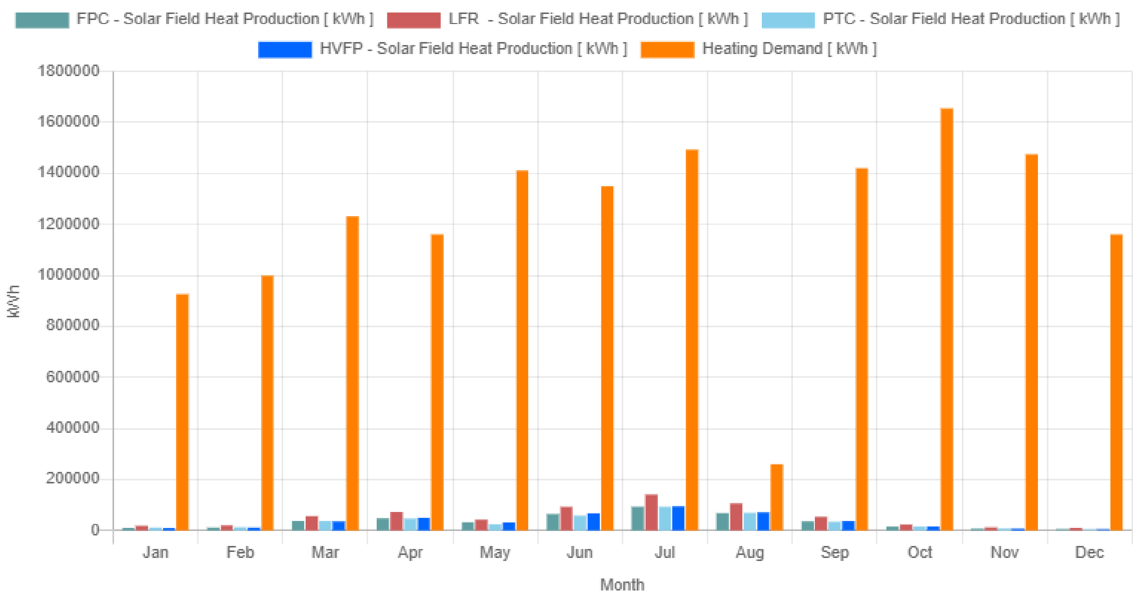

Figure 5: Comparison Monthly Heat Demand and Potential Solar Energy Input as Function of Technology and Storage Capacity

After having determined the potential solar heat production in the considered scenarios, the SHIP2FAIR replication tool starts carrying out a series of sensitivity analyses aimed at identifying the optimal size of the thermal energy storage required in combination with the collectors. The results of the optimization are:

- the solution with 827 m^2 of flat plate collectors is identified as best suitable, since it is the only one allowing a positive return on investment, although lower than 1;
- based on the LCOH analysis, the optimal storage size is identified as of 1,000 kWh, which provides a LCOH of 76.4 €/MWh; slightly lower LCOH values could be obtained with higher storage volumes but at the expense of a significant higher initial investment cost;
- the solution allows achieving a solar share over the total heat demand of 2.3%; other solutions could allow higher solar share values, up to 4.3%, but they are not economically profitable due to the higher investment needed;
- under a financial perspective, with an initial investment of around 370,000 €, the solution ensures a payback of 18.5 years and a ROI (intended as ratio between the NPV at the 25th year and the initial investment) of 0.59;

- the project allows avoiding GHG emissions for a total of 1,711 2,174 tCO2e over the lifetime (25 years), corresponding to 68 tCO_2e/y, i.e. 1.0% of the baseline emissions of the plant.
- the project allows avoiding GHG emissions for a total of 2,174 tCO2e over the lifetime (25 years), corresponding to 87 tCO_2e/y, i.e. 1.2% of the baseline emissions of the plant.

3.2 Case Study 2 – Chemical, Slovenia

Subject of the study is a chemical plant in Slovenia, whose raw material is constituted by natural gas and atmospheric nitrogen and whose main product is ammonia. Besides the use of natural gas as raw material (source of carbon), this fuel is also used for the production of heat required in the plant.

The plant uses energy in form of natural gas and electricity, which account for 97% (21,600,000 Nm^3/y, i.e. 207,144 MWh/y) and 3% (5,280 MWh/y) of the total final energy use, respectively. The greenhouse gases emissions of the plant are estimated at about 42,485 tCO_2e/year, 96% of which due to direct natural gas combustion and 4% of which indirectly due to electricity purchase from the grid.

Based on estimations done by the company, 69% of the steam produced by the boilers is at 180°C and 31% at 130°C.

The trend of hourly and monthly heat demand modelled with the SHIP2FAIR tool is presented respectively in Figure 6 and Figure 7.

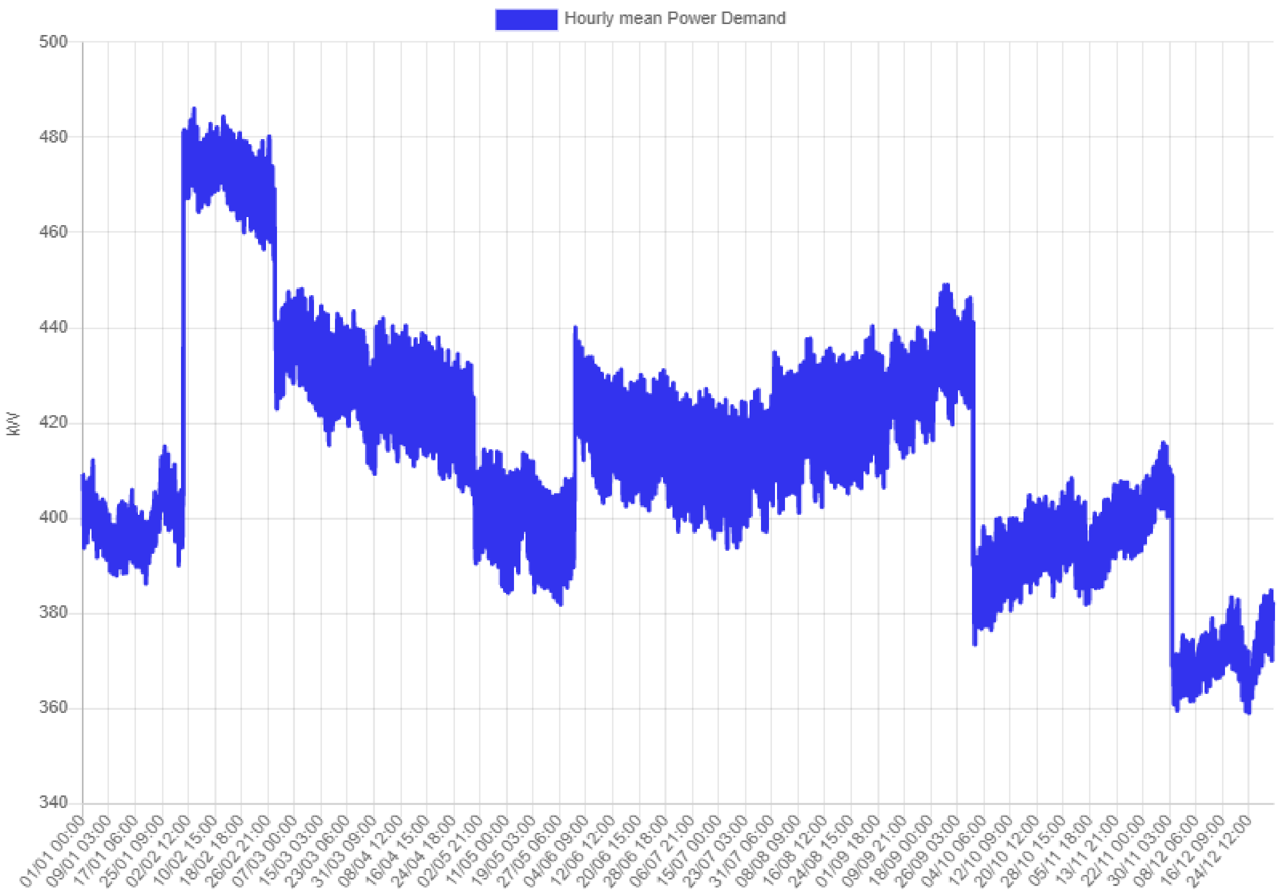

Figure 6: Modeling of Total Hourly Heat Demand

Figure 7: Modeling of Monthly Heat Demand and Breakdown among Processes

The roof of the industrial site has a total area is of 34,600 m^2 and is constituted by a series of two-pitched sloped roofs, oriented NW-SE and with inclination of 30°. No significant obstacles and sources of shading are present, neither significant space is required for other installations. Based on the preliminary information gathered, all the roof area is suitable for the installation of solar panels.

The monthly profiles of direct normal and global solar irradiance at the site are presented in Figure 8.

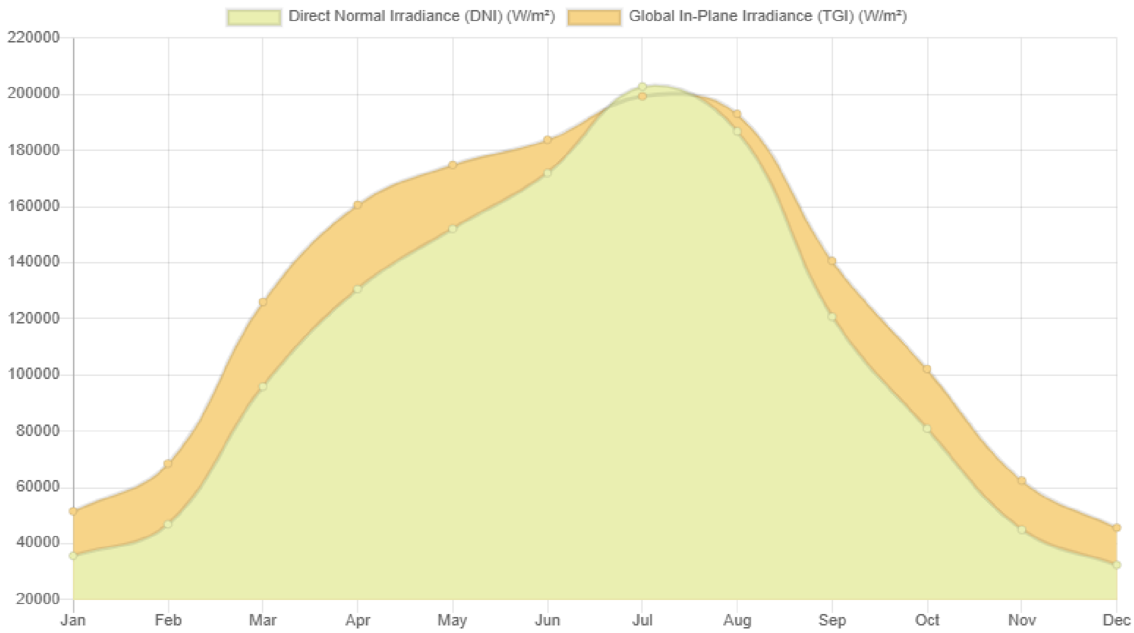

Figure 8: Direct Normal and Global In-Plane Solar Irradiance Monthly Profiles

The target plant requires for its processes steam at a temperature between 130 and 180°C. Based on this range of operational temperatures, in line with the matching carried out in SHIP2FAIR D2.1, three technologies are identified as potentially most appropriate and are briefly described below:

- high-vacuum flat plate collectors (HVFPC);
- evacuated tube collectors (ETC);
- linear Fresnel reflectors (LFR) with single-axis tracker.

Based on the algorithms implemented in the SHIP2FAIR replication tool the following maximum areas were considered for the different technologies of solar collectors:

- 19,226 m^2 for HVFPC;
- 27,713 m^2 for ETC;
- 25,981 m^2 for LFR.

The potential monthly thermal energy production of those solutions are compared with the monthly heating demand of the site in the chart in Figure 5.

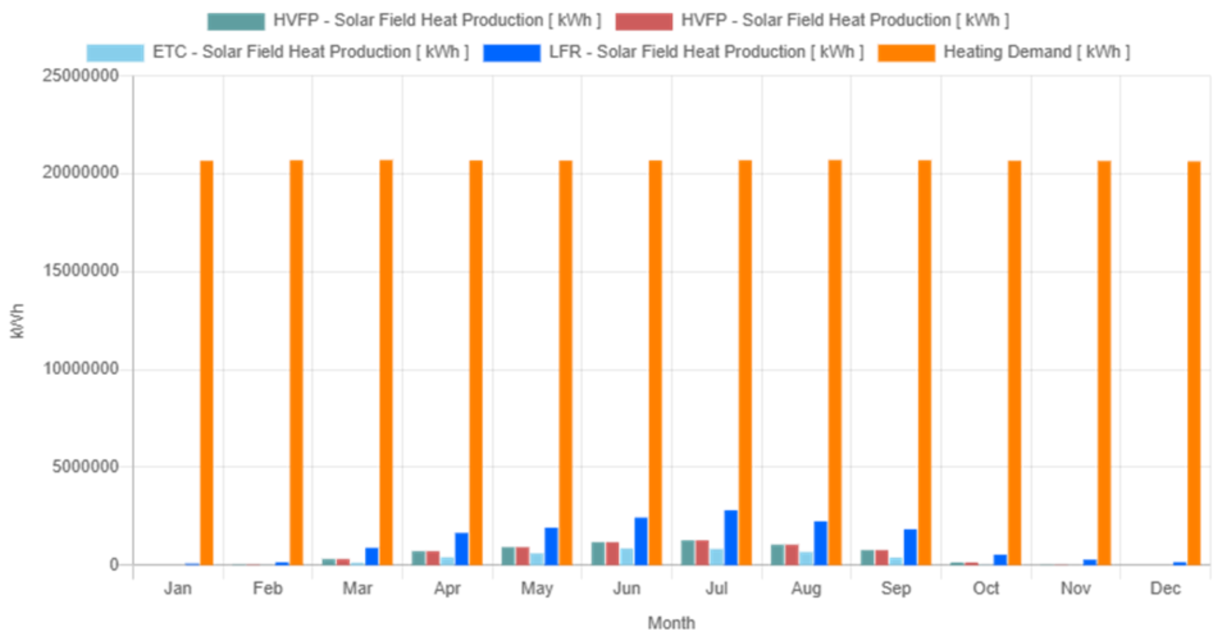

Figure 9: Comparison Monthly Heat Demand and Potential Solar Energy Input as Function of Technology and Storage Capacity

After having determined the potential solar heat production in the considered scenarios, the SHIP2FAIR replication tool starts carrying out a series of sensitivity analyses aimed at identifying the optimal size of the thermal energy storage required in combination with the collectors. The results of the optimization are:

- the solution with 25,981 m^2 of Linear Fresnel collectors is identified as best suitable, since it allows the lowest LCOH, 44.9 €/MWh, and the highest return on investment, although slightly lower than 1;
- due to the significantly lower energy production of the solar thermal plants compared to the thermal energy demand of the site, a storage system is not required, thus no optimization is carried out with reference to the parameter "thermal storage size";
- the solution allows achieving a solar share over the total heat demand of 6%;

- under a financial perspective, with an initial investment of around 7.4 million €, the solution ensures a payback of 11 years and a ROI (intended as ratio between the NPV at the 25th year and the initial investment) of 0.847;
- the project allows avoiding GHG emissions for a total of 57,868 tCO_2e over the lifetime (25 years), corresponding to 2,315 tCO_2e/y, i.e. 5.4% of the baseline emissions of the plant.

3.3 Case Study 3 – Office/Laboratory, Italy

The site subject of this study is a research laboratory, carrying out several activities in the mechatronic field that require in addition to heat for space heating and sanitary hot water, also steam for laboratory activities.

The plant uses energy in form of natural gas and electricity, which account for 34% (433,000 Nm^3/y, i.e. 4,153 MWh/y) and 66% (8,046 MWh/y) of the total final energy use, respectively. The greenhouse gases emissions of the plant are estimated at about 2,809 tCO_2e/year, 36% of which due to direct natural gas combustion and 64% of which indirectly due to electricity purchase from the grid.

Based on estimations carried out in the energy audit of the plant, 61% of the heat demand is due to steam production for laboratories and 39% to space heating.

The trend of hourly and monthly heat demand modelled with the SHIP2FAIR tool is presented respectively in Figure 10 and Figure 11.

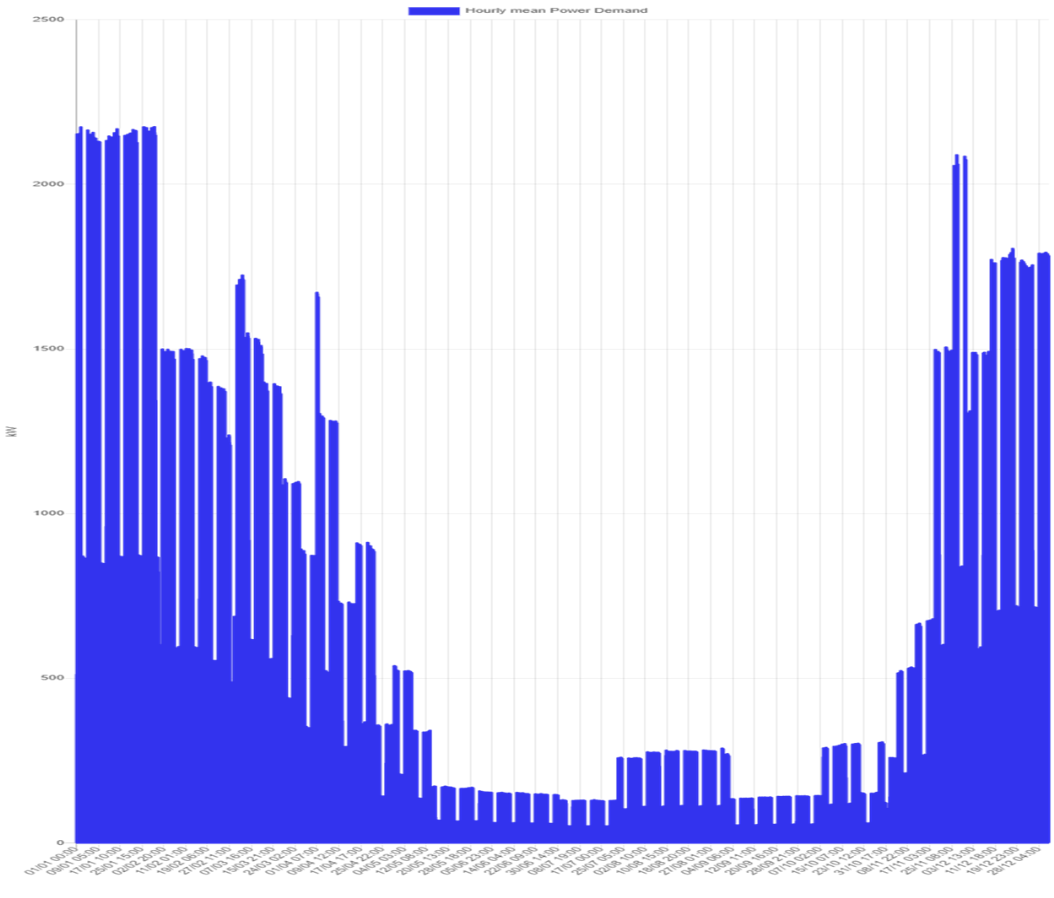

Figure 10: Modeling of Total Hourly Heat Demand

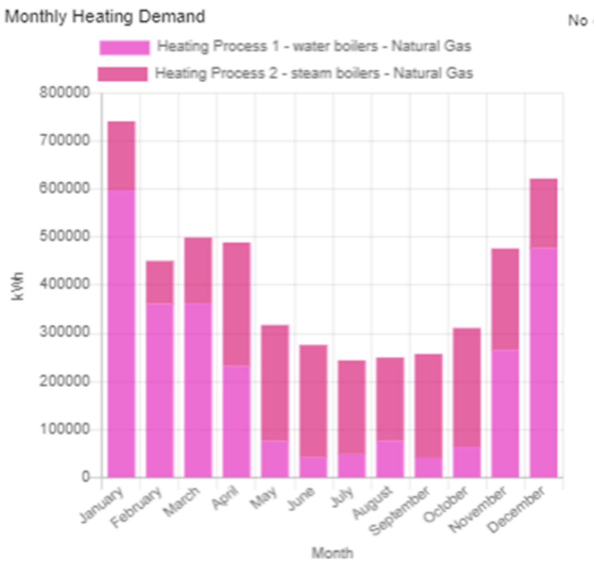

Figure 11: Modeling of Monthly Heat Demand and Breakdown among Processes

The roof of the building has a total area of 300 m^2 and is constituted by a series of flat roofs, oriented towards SW. No significant obstacles and sources of shading are present, neither significant space is required for other installations. Based on the preliminary information gathered, all the roof area is suitable for the installation of solar panels.

The monthly profiles of direct normal and global solar irradiance at the site are presented in Figure 12.

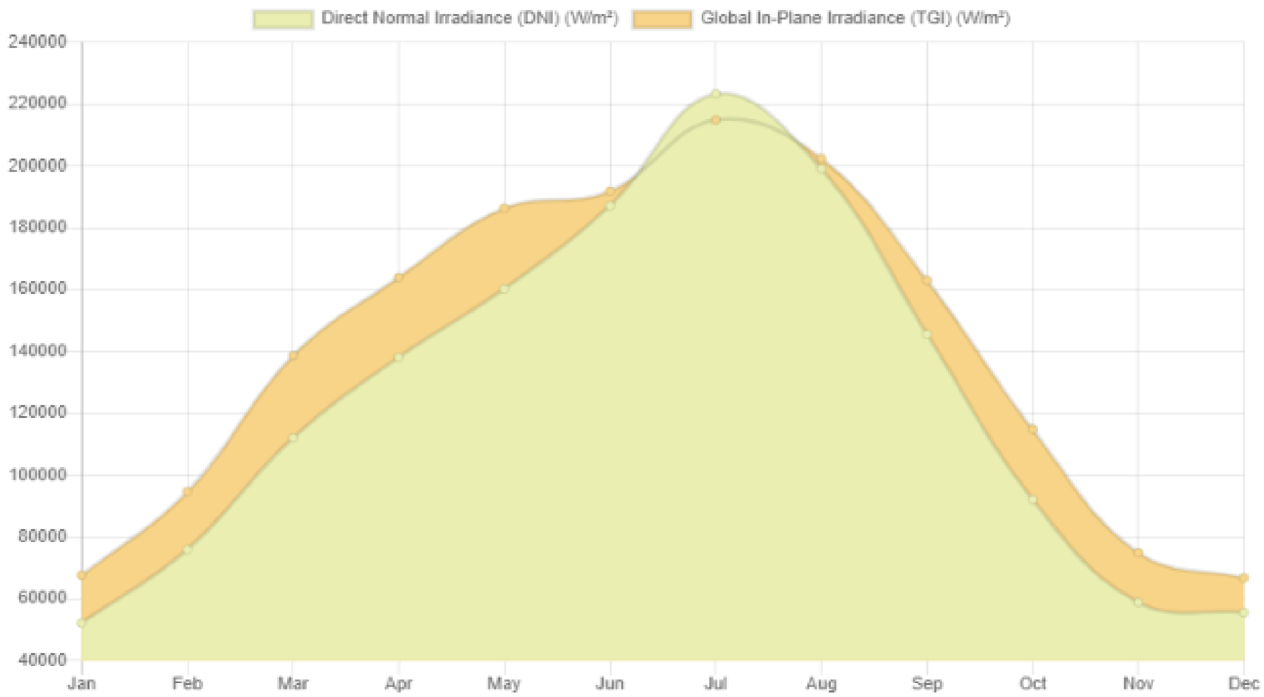

Figure 12: Direct Normal and Global In-Plane Solar Irradiance Monthly Profiles

The target plant requires for its processes hot water at 90°C and steam at 160°C. Based on this range of operational temperatures, in line with the matching carried out in SHIP2FAIR D2.1, the technologies identified as potentially most appropriate are:

- high-vacuum flat plate collectors (HVFPC);
- linear Fresnel reflectors (LFR) with single-axis tracker.

Based on the algorithms implemented in the SHIP2FAIR replication tool the following maximum areas were considered for the different technologies of solar collectors:

- 133 m^2 for HVFPC;
- 180 m^2 for LFR.

The potential monthly thermal energy production of those solutions are compared with the monthly heating demand of the site in the chart in Figure 13.

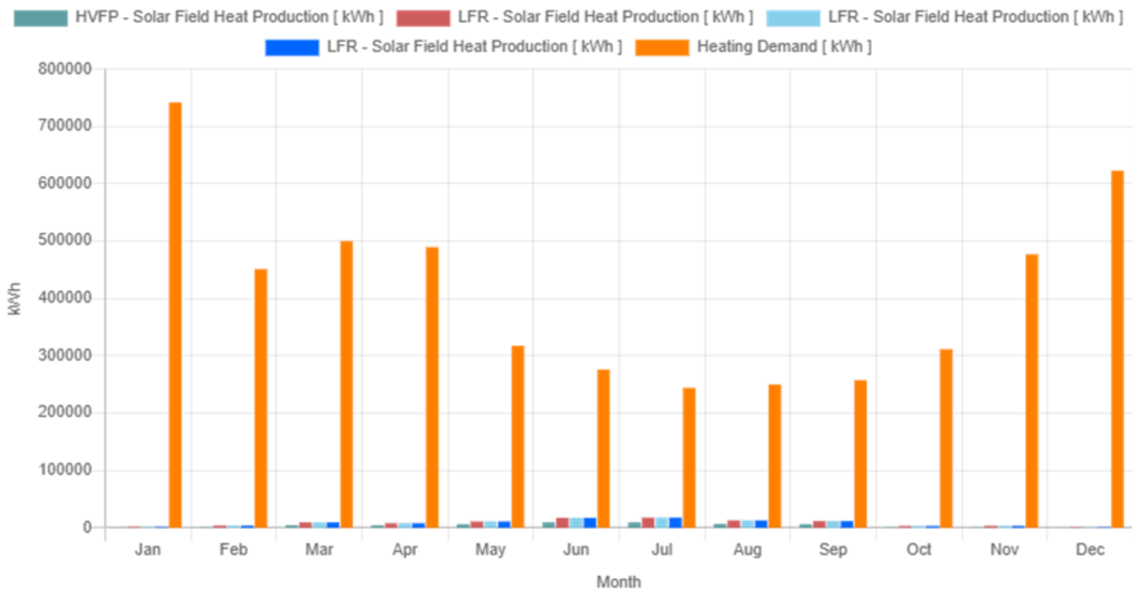

Figure 13: Comparison Monthly Heat Demand and Potential Solar Energy Input as Function of Technology and Storage Capacity

After having determined the potential solar heat production in the considered scenarios, the SHIP2FAIR replication tool starts carrying out a series of sensitivity analyses aimed at identifying the optimal size of the thermal energy storage required in combination with the collectors. The results of the optimization are:

- the solution with 180 m^2 of Linear Fresnel collectors with 150 kWh of thermal energy storage is identified as best suitable, since it allows the lowest LCOH, 49.8 €/MWh, and the highest return on investment, although lower than 1;
- the solution allows achieving a solar share over the total heat demand of 2%;
- under a financial perspective, with an initial investment of around 50,000 €, the solution ensures a payback of 12.1 years and a ROI (intended as ratio between the NPV at the 25th year and the initial investment) of 0.661;
- the project allows avoiding GHG emissions for a total of 434 tCO_2e over the lifetime (25 years), corresponding to 17.4 tCO_2e/y, i.e. 0.6% of the baseline emissions of the plant.

3.4 Case Study 4 – Wastewater Treatment, France

Subject of the study is a wastewater treatment plant in France. This replication study has been the first to be completed at the end of 2021, thus charts and results look different than the other studies, due to the fact that the Replication Tool was not yet in its final shape.

The plant uses energy in form of natural gas and electricity, respectively for 1,079 MWh/y and 4,893 MWh/y. Based on estimations carried out in the energy audit of the plant, 75% of the heat required in the plant is due to process, i.e. PCO, PCM and process heating, and is covered by an electrical boiler.

The trend of hourly heat demand modelled with the SHIP2FAIR tool is presented in Figure 14.

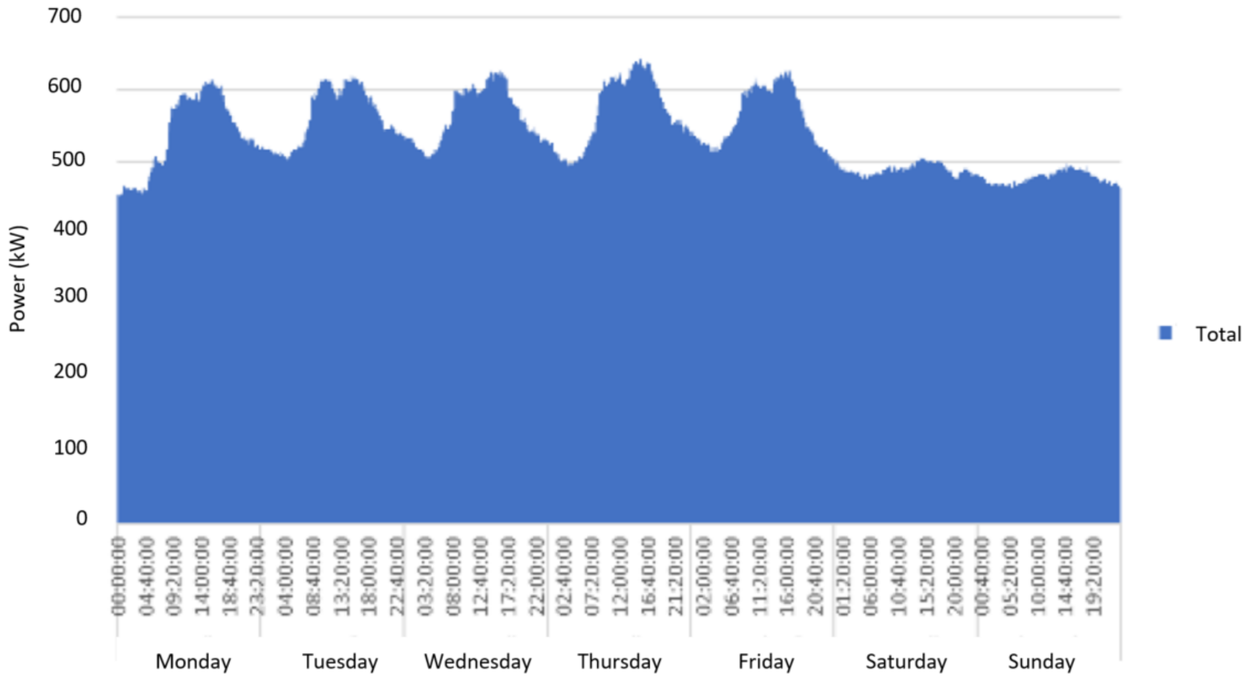

Figure 14: Modeling of Total Hourly Heat Demand

The roofs of the industrial site include a series of roofs with orientation between N-E and S-W and with inclination between 11° and 13°. Only a chimney could be a source of shading but its impact is neglected; no significant space is required for other installations. Based on the preliminary information gathered, all the roof area is suitable for the installation of solar panels.

The monthly profiles of direct normal and global solar irradiance at the site are presented in Figure 15.

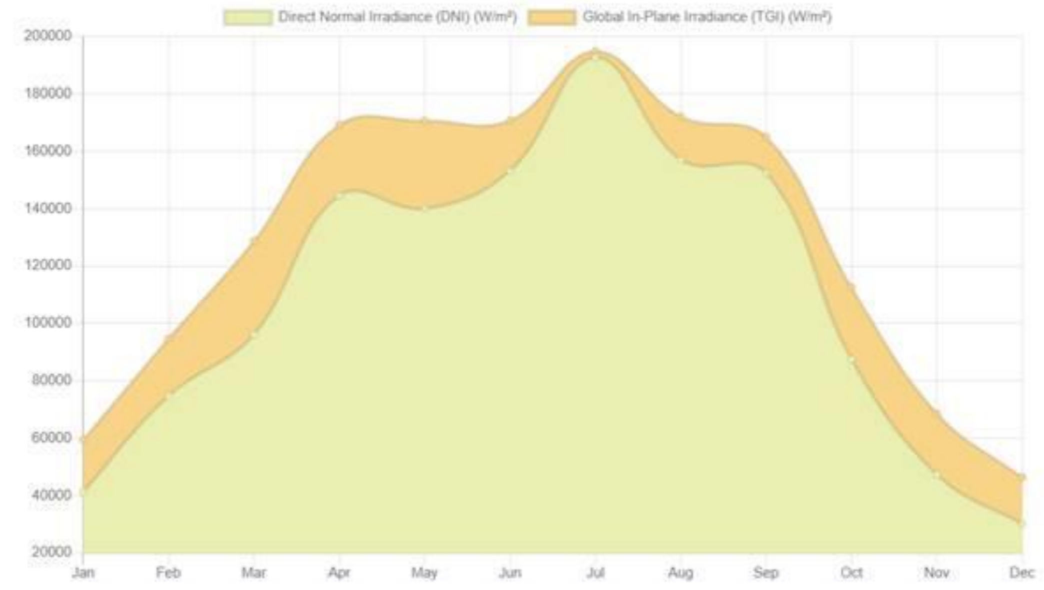

Figure 15: Direct Normal and Global In-Plane Solar Irradiance Monthly Profiles

The target plant requires for its processes heat in form of hot water at 70-80°C. Based on this range of operational temperatures, in line with the matching carried out in SHIP2FAIR D2.1, three technologies are identified as potentially most appropriate and are briefly described below:

- flat plate collectors (FPC);
- evacuated tube collectors (ETC);
- high vacuum flat plate collectors (HVFPC).

Based on the algorithms implemented in the SHIP2FAIR replication tool the following maximum areas were considered for the different technologies of solar collectors:

- 250 m^2 for HVFPC;
- 300 m^2 for ETC;
- 200 m^2 for LFR.

The HVFPC is the most promising technology, the LCOH is 75.3 €/MWh. Despite the orientation and the inclination of the roof, it is possible to place the plane of the collectors at the optimal orientation and absolute inclination, which is to say to place the rows in diagonal on the roof. Although this solution is more difficult to implement and generates an additional cost to the installation, the expected gain is about 5 k€.

The total available surface of 270 m^2 on these roofs allows it to benefit from an optimal LCOH. Indeed, by taking a surface of collectors of 135 m^2 (occupation rate of 50%) to 190 m^2 (occupation rate of 70%), we place ourselves in the zone where the LCOH is optimal. An occupancy rate of 70% generates 1% of annual shading, which impacts the LCOH by 1% but allows to benefit from a solar fraction of 50% against 35% for an occupancy rate of 50%. It would be even possible to increase the occupancy rate beyond that to benefit from a higher solar fraction, but it will still affect the LCOH due to shading. The optimal storage volume would be 28 m^3 for 135 m^2 of installed TVP Solar collectors (50% occupancy) and 40 m^3 for 190 m^2, which correspond respectively to capacities of 1 MWh and 1.4 MWh and operating times at nominal process speed of 11.5 h and 16 h respectively. Thus, the storage will contribute to about 2/3 of the solar contribution.

3.5 Case Study 5 – Dairy, Spain

Subject of the study is a dairy industry in Spain, producing goat's milk concentrate from eight goat cooperatives.

For heat-related processes, the plant uses energy in form of natural gas for around 161,000 Nm^3/y, corresponding to 1,632 MWh/y. The greenhouse gases emissions of the plant are estimated at about 404.25 tCO_2e/y.

The heat required for these processes is produced in two low-temperature superheated water boilers, which have a nominal output of 1,300 kW and 1,100 kW, respectively. They operate by setpoint, one of them at 105º and the other at 102°C. According to the information provided by the Company, 40% of steam produced by boilers is used for pasteurisation and the remaining 60% for cleaning (CIP). Both processes are carried out at a temperature of 85°C.

The trend of hourly and monthly heat demand modelled with the SHIP2FAIR tool is presented respectively in Figure 16 and Figure 17.

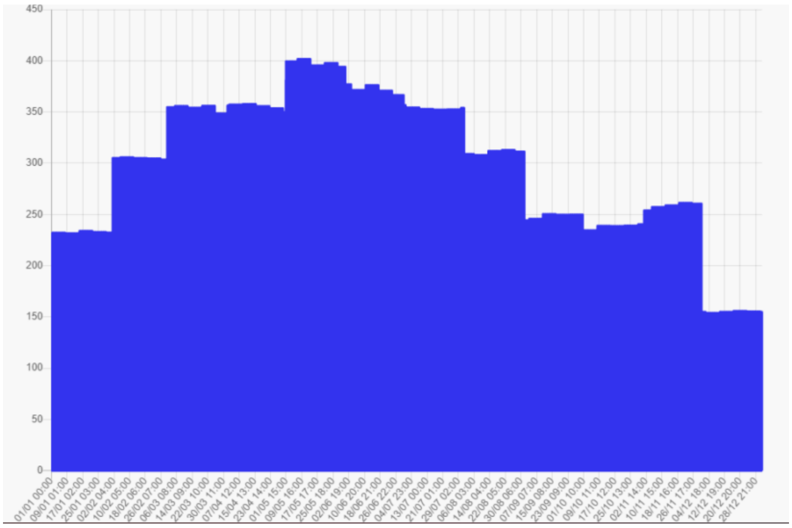

Figure 16: Modeling of Total Hourly Heat Demand

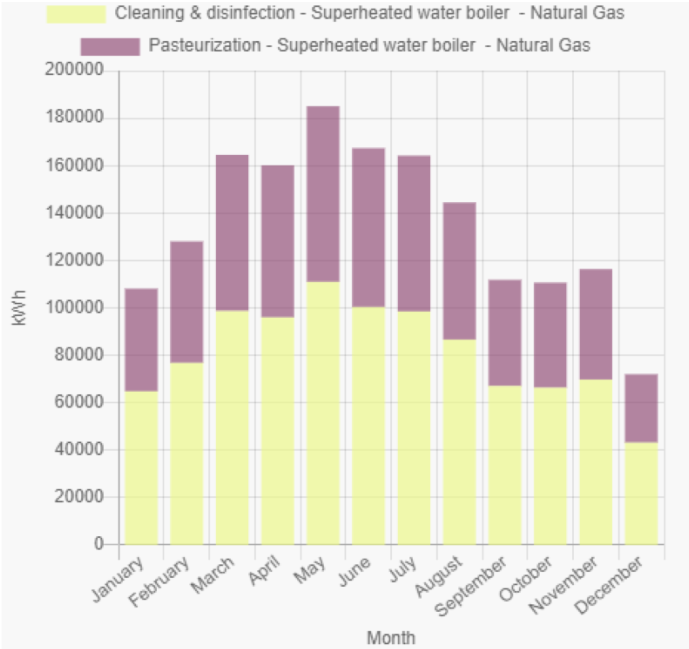

Figure 17: Modeling of Monthly Heat Demand and Breakdown among Processes

The area available for the location of the solar installation is the plot annexed to the plant. It has a total area of approximately 4,400 m^2 and there are no significant obstacles or shadings. It is currently available and there are no plans to locate other installations in this space, so it is considered to be suitable for the solar installation.

The monthly profiles of direct normal and global solar irradiance at the site are presented in Figure 18.

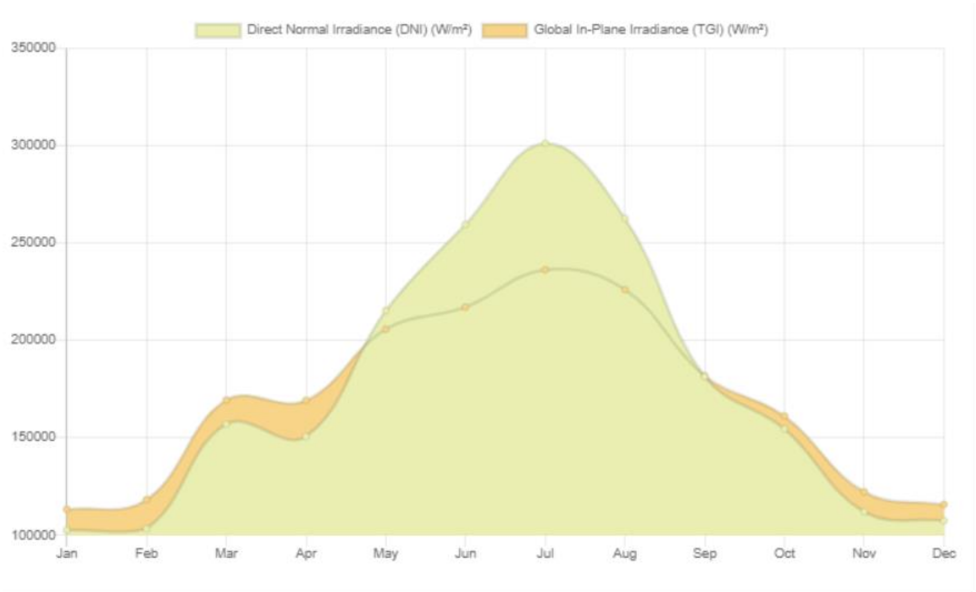

Figure 18: Direct Normal and Global In-Plane Solar Irradiance Monthly Profiles

The target plant requires for its processes of pasteurization and cleaning (CIP) heat in form of hot water at 85°C. Based on this operational temperature, in line with the matching carried out in SHIP2FAIR D2.1, three technologies are identified as potentially most appropriate and are briefly described below:

- High Vacuum Flat Panels (HVFPs) ("Thermal Vacuum Power");
- Linear Fresnel reflectors (LFR);
- Flat Solar Collectors (FPC).

Based on the algorithms implemented in the SHIP2FAIR replication tool and proposing the use of the entire area available for the solar installation (4,400 m2), the following maximum areas were considered for the different technologies of solar collectors:

- 1,665 m^2 for HVFPs (High Vacuum Flat Panels);
- 2,250 m^2 for LFR (Linear Fresnel Reflectors).
- 1,665 m^2 for FPC (Flat Solar Collectors).

The potential monthly thermal energy production of those solutions are compared with the monthly heating demand of the site in the chart in Figure 5Figure 19.

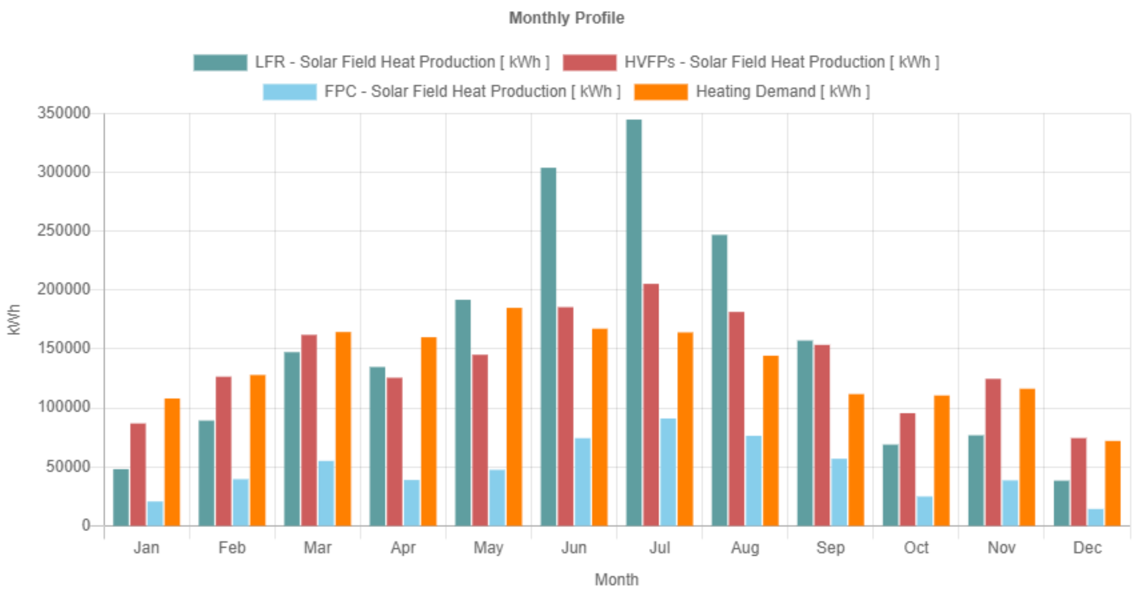

Figure 19: Comparison Monthly Heat Demand and Potential Solar Energy Input as Function of Technology and Storage Capacity

After having determined the potential solar heat production in the considered scenarios, the SHIP2FAIR replication tool starts carrying out a series of sensitivity analyses aimed at identifying the optimal size of the thermal energy storage required in combination with the collectors. The results of the optimization are:

- the 1,665 m^2 High Vacuum Flat Panels solution appears to be the most suitable solution as it has a better return on investment.
- based on the LCOH analysis, it is identified that the optimal storage size is 2,222 kWh, which gives an LCOH of 17.46 €/MWh;
- the solution makes it possible to achieve a solar share of total heat demand of almost 78.7 %;
- from a financial point of view, with an initial investment of around 999,000 € (assuming a CAPEX of 600 €/m^2 for HVFPs), the solution guarantees a payback period of 3.4 years and an ROI (understood as the ratio between the NPV after 25 years and the initial investment) of 3.2;
- the project will avoid GHG emissions totalling 7,518.2 tCO_2e over its useful life (25 years), which corresponds to 300.73 tCO_2e/year, i.e. 74.76 % of the plant's baseline emissions.

3.6 Case Study 6 – Meat Processing, France

Subject of the study is a meat processing plant in France, specialized in the manufacture and distribution of high-quality fresh meat products (cooked ham and dry sausage) for professionals in the food industry. The total annual heat demand of the plant, covered by natural gas, is of 14,800 MWh/y.

The current thermal energy system of the plant is constituted by a steam generation boiler (covering 85% of the needs) and a water heater (at 75°C) and three water boilers for tank cooking (60°C) and bain marie (80°C). As concerns steam, it is then used mainly for:

- cooking ham at 70°C (steam is lost, without condensate return);
- pasteurisation at 96°C via a tubular exchanger (with condensate recovery);
- sanitary hot water production at about 55°C for 250 m^3/d;
- water heating for process washing systems.

The hourly trend of heat demand for each day of the year is presented in Figure 20 (values in kW).

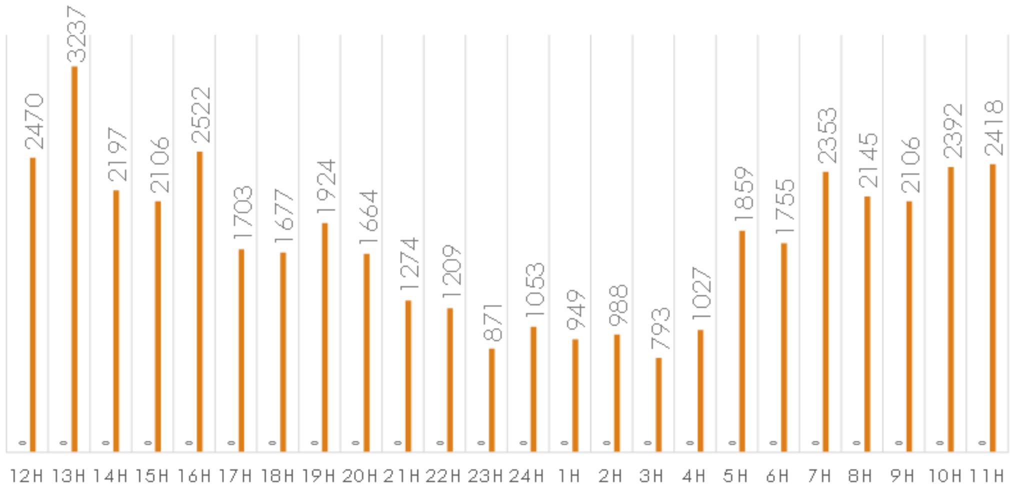

Figure 20: Modeling of Hourly Heat Demand

The identified space for the installation of the solar systems is a land plot adjacent to the industrial site with a total area of approximately 4,000 m^2.

The monthly profiles of direct normal and global solar irradiance at the site are presented in Figure 21.

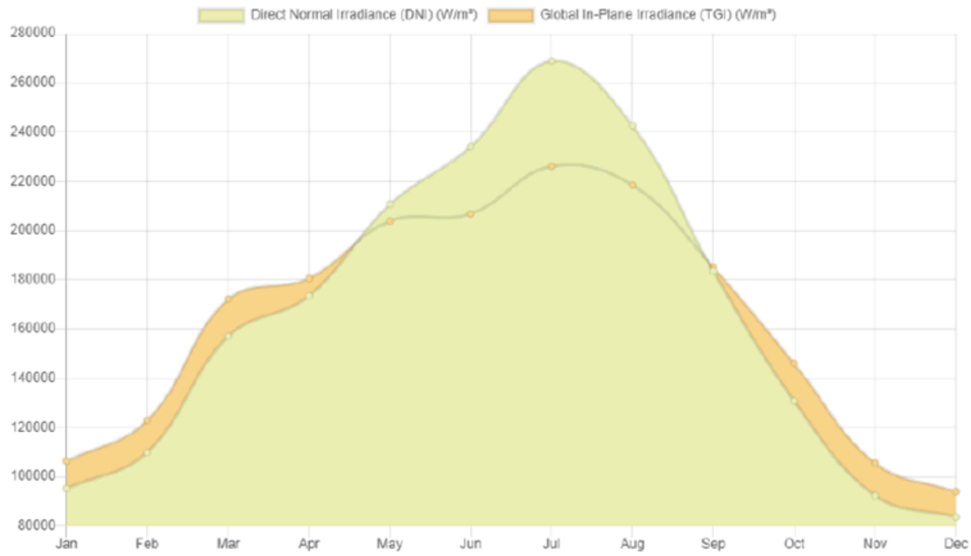

Figure 21: Direct Normal and Global In-Plane Solar Irradiance Monthly Profiles

The target plant requires for its processes heat at a relative high temperature range ≈140°C. Based on this range of operational temperatures, the level of solar irradiance in the location and in line with the matching carried out in SHIP2FAIR D2.1, the following solar thermal technologies are identified as potentially most appropriate:

- High vacuum flat plate collectors (HVFP);
- Evacuated Tubes Collectors (ETC);
- Linear Fresnel reflector (LFR);
- Parabolic Troughs Collectors (PTC).

Based on the land availability (4,000 m^2) and heat demand profile, the following gross areas are considered for the solar thermal systems:

- 2,200 m^2 for HVFPs (High Vacuum Flat Panels);
- 2,200 m^2 ETC (Evacuated Tubes Collectors);
- 3,000 m^2 for LFR (Linear Fresnel Reflectors);
- 2,000 m^2 PTC (Parabolic Trough Collectors).

The potential monthly thermal energy production of those solutions are compared with the monthly heating demand of the site in the chart in Figure 22.

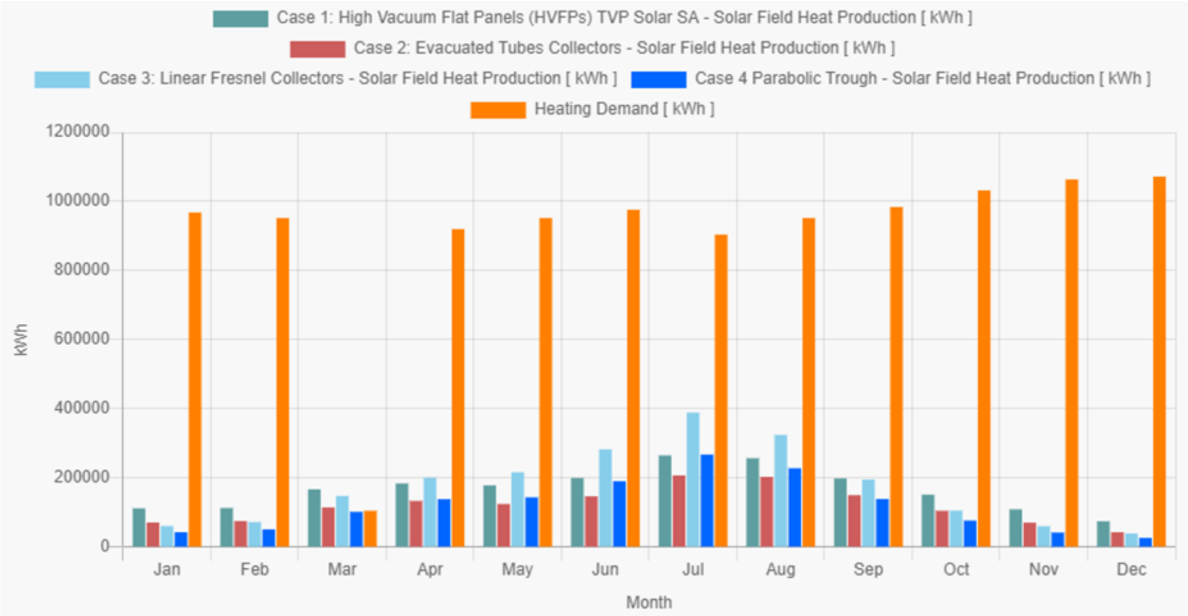

Figure 22: Comparison Monthly Heat Demand and Potential Solar Energy Input as Function of Technology and Storage Capacity

After having determined the potential solar heat production in the considered scenarios, the SHIP2FAIR replication tool starts carrying out a series of sensitivity analyses aimed at identifying the optimal size of the thermal energy storage required in combination with the collectors.

The preferred installation of the solar field is to place the collectors' rows with an absolute inclination of 35° (in the case of non-concentrated technologies) facing south. There is no gain from the point of view of inter-row shading to have an occupancy rate lower than 50%.

The total available surface on the ground of 4,000 m²; by taking a surface of collectors of 2,200 m² (occupation rate of 55.5%), an optimal LCOH is obtained, considering production of hot water at 95°C.

Based on the simulation results, among the four technologies HVFP is the most promising one, delivering the lowest LCOH at 44 €/MWh and producing around 2,000 MWh/y of thermal energy. HVFPs also demonstrate the lower payback period, of 12-13 years. The actual payback period may be much lower as the price of natural gas has experienced a multifold increase over the last year.

3.7 Case Study 7 – Brewery, Spain

Subject of the study is a beer production plant in Spain, producing 700 million liters per year in a 430,000 m^2 industrial site and having a total heat demand of 92,796 MWh/y.

Suitable processes for solar thermal application are mashing, cleaning and disinfection, bottle washing, pasteurization, space heating, and wastewater heating. Mashing takes place at 100˚C, bottle washing, and cleaning and disinfection take place at 85˚C, pasteurization at 70˚C, space heating at 75˚C, and wastewater heating at 35˚C. The heat required for these processes is produced in three superheated water boilers, one of them with a nominal potential of 23 MW and the other two with 18 MW. In addition, two hot water boilers with a nominal power of 2 MW and 1.5 MW respectively are installed at the site. According to the information provided by the company, the three superheated water boilers provide heat to the mashing process (44% of consumption), bottle washing (9%), pasteurization (8%) and space heating (0.2%). The water boilers provide hot water at 35˚C to the wastewater heating process, but the consumption of this process is only 1.75%.

The trend of hourly heat demand modelled with the SHIP2FAIR tool is presented in Figure 23.

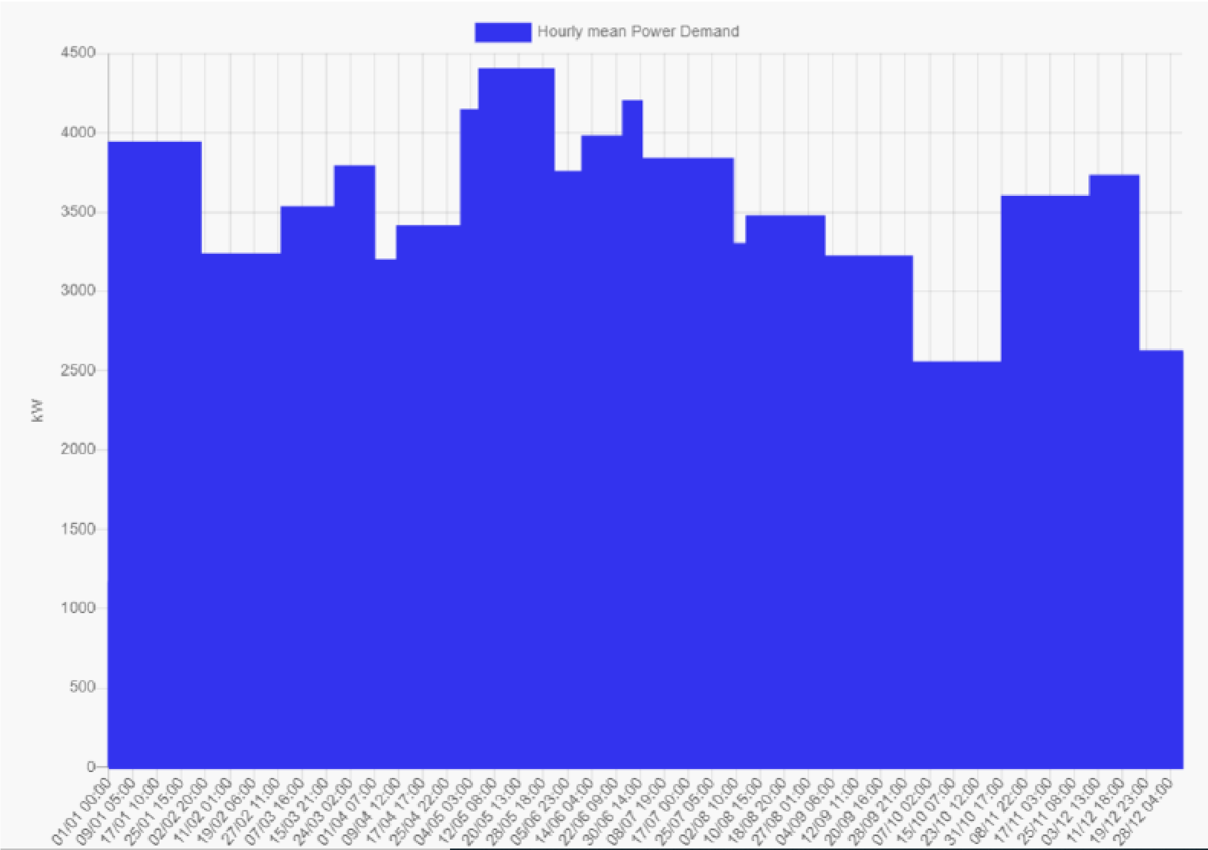

Figure 23: Modeling of Total Hourly Heat Demand

The available area for the installation of solar thermal collectors is 11,850 m^2. It has been assumed that the type of installation is a flat roof, and any corrective factors have been considered, i.e no obstacles, no shading, and no need for maintenance space.

The monthly profiles of direct normal and global solar irradiance at the site are presented in Figure 24.

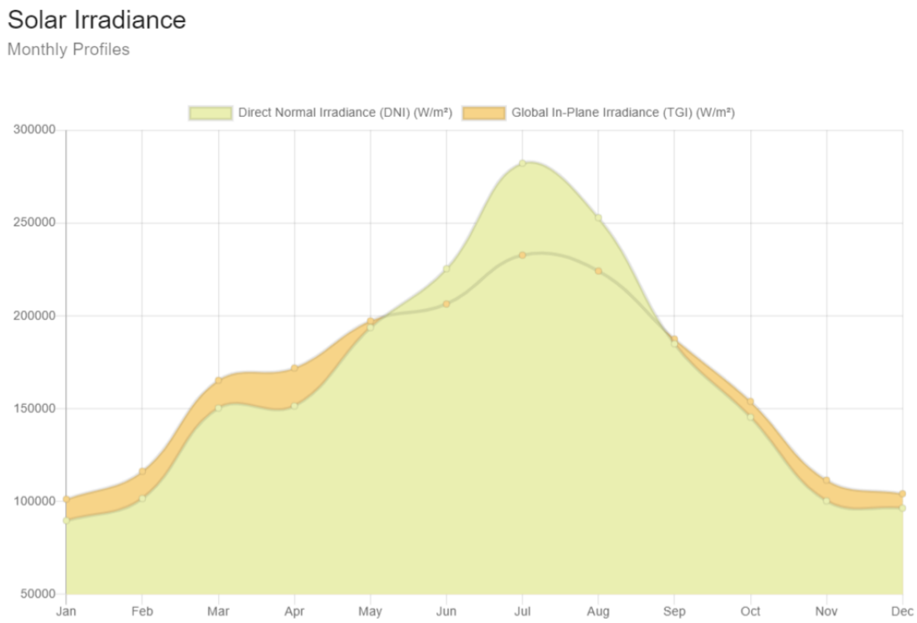

Figure 24: Direct Normal and Global In-Plane Solar Irradiance Monthly Profiles

The analysed processes of this plant require heat in form of hot water at temperature levels from 100 to 35˚C. Based on these requirements and the analysis of solar thermal technologies carried out in SHIP2FAIR D2.1, four technologies are identified as potentially most appropriate:

- Flat Solar Collectors (FPC);
- High Vacuum Flat Panels (HVFPs) ("Thermal Vacuum Power");
- Evacuated tubes collectors (ETC);
- Evacuated tubes collectors-Viessmann Vitosol type.

Based on the algorithms implemented in the SHIP2FAIR replication tool the following maximum areas were considered for the different technologies of solar collectors:

- 6,577 m^2 for FPC;
- 6,577 m^2 for HVFP;
- 9,480 m^2 for ETC;
- 11,850 m^2 for ETC-Viessman Vitosol.

The potential monthly thermal energy production of those solutions are compared with the monthly heating demand of the site in the chart in Figure 25.

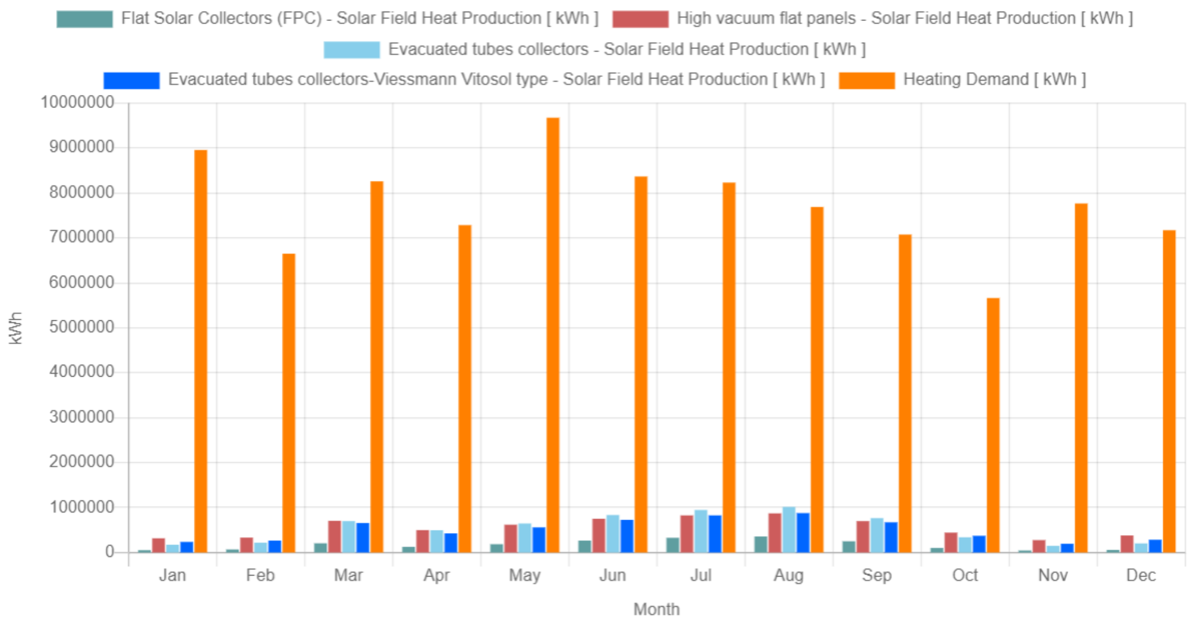

Figure 25: Comparison Monthly Heat Demand and Potential Solar Energy Input as Function of Technology and Storage Capacity

After having determined the potential solar heat production in the considered scenarios, the SHIP2FAIR replication tool starts carrying out a series of sensitivity analyses aimed at identifying the optimal size of the thermal energy storage required in combination with the collectors. The results of the optimization are:

- due to the high heat demand of the plant, it is not possible to propose a feasible system with thermal energy storage + solar collectors. The results from the Simulation Modules confirm this hypothesis, showing that the storage rises the levelized cost of heat of the whole system;
- an installed area of 6,577 m^2 High Vacuum Flat Panels (HVFP) seems to be the best solution according to the results. This technology provides the maximum solar production considering heat demand, with an annual production of 6,719.98 MWh;
- the ratio between yearly solar heat production/collector gross surface for the HVFP is also the highest for the four cases (1,022 kWh/m^2). Showing that this technology has the best annual performance regarding solar share;
- the initial investment for the installation of HVFP, based on the result collector gross surface of 6,577 m^2, is around 3,946,200 € (considering a CAPEX of 600 €/m^2). The financial results show a payback period of 5.6 years, and a ROI of 3.48;
- this technology provides a total GHG emission reduction over lifetime of 26,490.5 tCO_2e;
- the annual natural gas savings, based on the annual production of this technology, may reach 523,770 Nm^3, which is a 7% reduction of natural gas for heating purposes.

3.8 Case Study 8 – Food, Jordan

The plant focus of the replication study is a food company located in Jordan, in which high-quality halva, sweetness, and roasted sesame are produced. The company uses the best raw material available in the market to provide luxury and high-quality products for their clients. For this aim, the best tools, and equipment are in use in the production lines. For instance, in the case of high-quality sesame, five stages of screening, roasted, and milled are implemented.

The plant uses energy in form of diesel. The annual heat demand of 245,000 MWh results from the fuel energy demand multiplied by the boiler efficiency. The electricity demand is unknown. Based on specific GHG emission factor of diesel of 0.2664 tCO_2e/MWh, the annual GHG emissions considering the only thermal demand, reach 932 tCO_2e/a.

Based on information provided by the Company, 100% of the thermal demand is in form of steam at 175°C. The trend of hourly heat demand modelled with the SHIP2FAIR tool is presented in Figure 26.

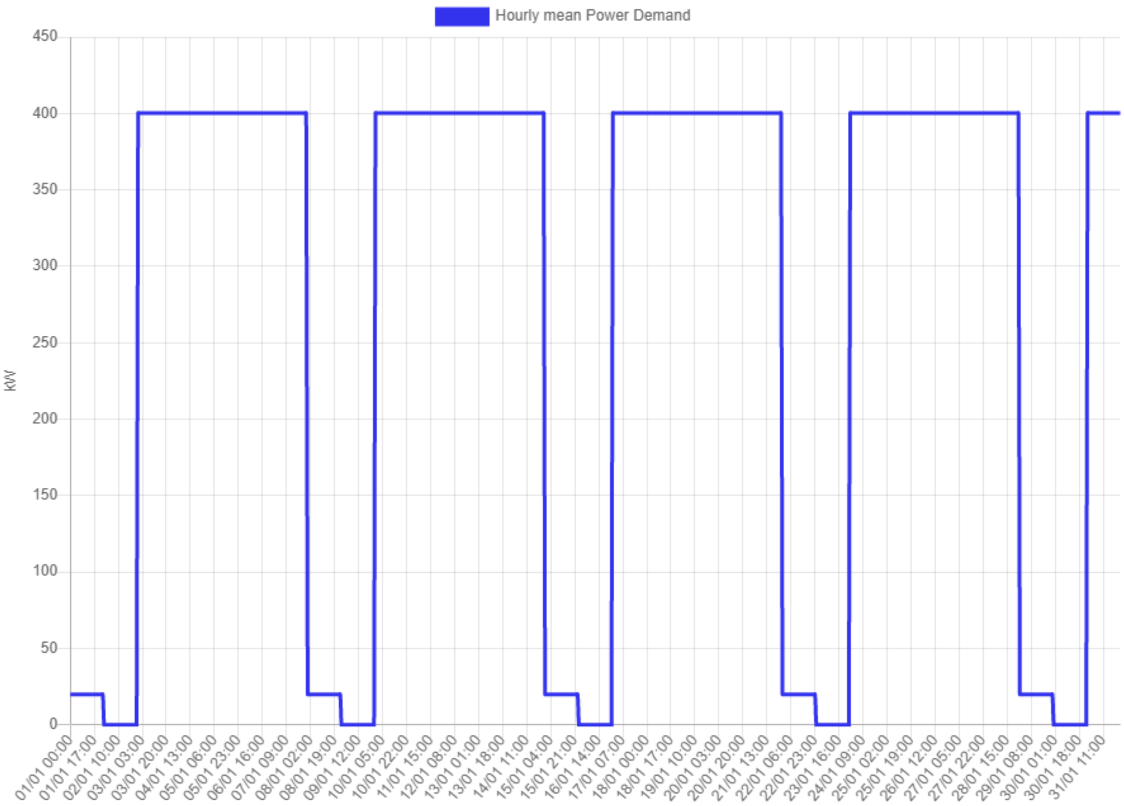

Figure 26: Modeling of Total Hourly Heat Demand

The company has availability of a free area of 2.955 m^2 next to the plant. No significant obstacles and sources of shading are present, and neither significant space is required for other installations. Based on the information approved by the client, the full ground area is suitable for solar installation.

The monthly profiles of direct normal and global solar irradiance at the site are presented in Figure 27.

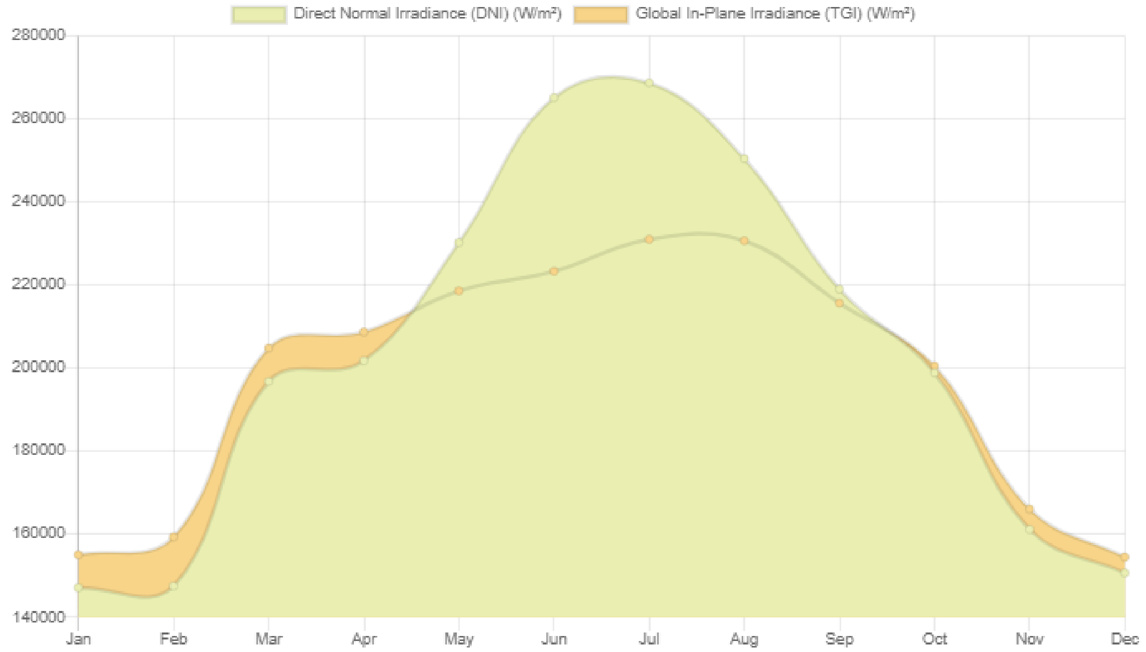

Figure 27: Direct Normal and Global In-Plane Solar Irradiance Monthly Profiles

The target plant requires for its processes heat in form of steam at 175°C. Based on this operational temperature, in line with the matching carried out in SHIP2FAIR D2.1, three technologies are identified as potentially most appropriate and are briefly described below:

- Parabolic Through collectors (PTC)
- High Vacuum Flat Panels (HVFPs);
- Linear Fresnel reflectors (LFR).

Based on the algorithms implemented in the SHIP2FAIR replication tool the following maximum collector gross areas were determined to fit on the available ground area for the different technologies of solar collectors:

- 1,478 m^2 for PTC;
- 1,640 m^2 for HVFPs;
- 2,216 m^2 for LFR.

The potential monthly thermal energy production of those solutions are compared with the monthly heating demand of the site in the chart in Figure 28.

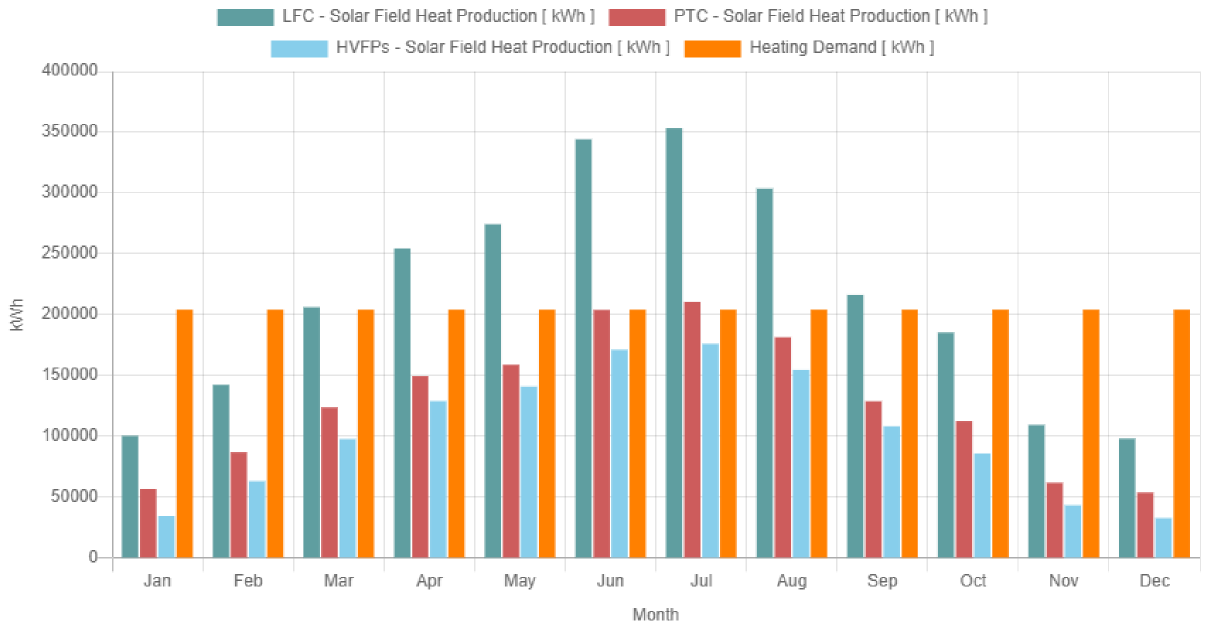

Figure 28: Comparison Monthly Heat Demand and Potential Solar Energy Input as Function of Technology and Storage Capacity

After having determined the potential solar heat production in the considered scenarios, the SHIP2FAIR replication tool starts carrying out a series of sensitivity analyses aimed at identifying the optimal size of the thermal energy storage required in combination with the collectors. The results of the optimization are:

- the Fresnel collector clearly the favourable collector type and reaches the best results of the three technologies in all KPIs;
- based on the LCOH analysis, the optimal storage size is identified as of 5 MWh, which provides an LCOH of 51 €/MWh; even with a significantly bigger storage of 10 MWh the LCOH is only slightly higher with 55 €/MWh;
- the solar share reaches up to 80.9 %; the smaller storage of 5 MWh reduces the solar share to 75.6 %;
- the Fresnel system reaches a payback of 5.2 years without consideration of funding (with a 5 MWh storage capacity). With the 10 MWh storage capacity the payback time is 5.5 years;
- the emissions savings account to 14,514 tCO_2e over the lifetime (25 years), with the biggest storage capacity.

3.9 Case Study 9 – Chemical, Spain

The site subject of the study is a world leader in the chemical sector; its site in Spain is located in the most important chemical cluster in the south of Europe and produces chemical products and chemical precursors for the industrial sector. The production is used mainly for industrial and household cleaners, personal care products, emulsionants, and others. Due to its coordinates, the location accounts for a high direct normal solar irradiation, which is favorable for concentrating solar technologies.

The plant groups several processes, running 24/7. The analyzed process works at 195°C with superheated steam at a pressure of 13 bar. Currently, the principal energy source is based on fossil fuels.

The monthly fuel demand is entered as input in the replication tool; the sum of energy consumed in form of natural gas is 16,930 MWh per year. Based on specific GHG emission factor of natural gas, of 200.88 $kgCO_2e/MWh$, the annual GHG emissions associated to natural gas consumption reach 3401 tCO_2e/y.

The trend of hourly and monthly heat demand modelled with the SHIP2FAIR tool is presented respectively in Figure 29 and Figure 30.

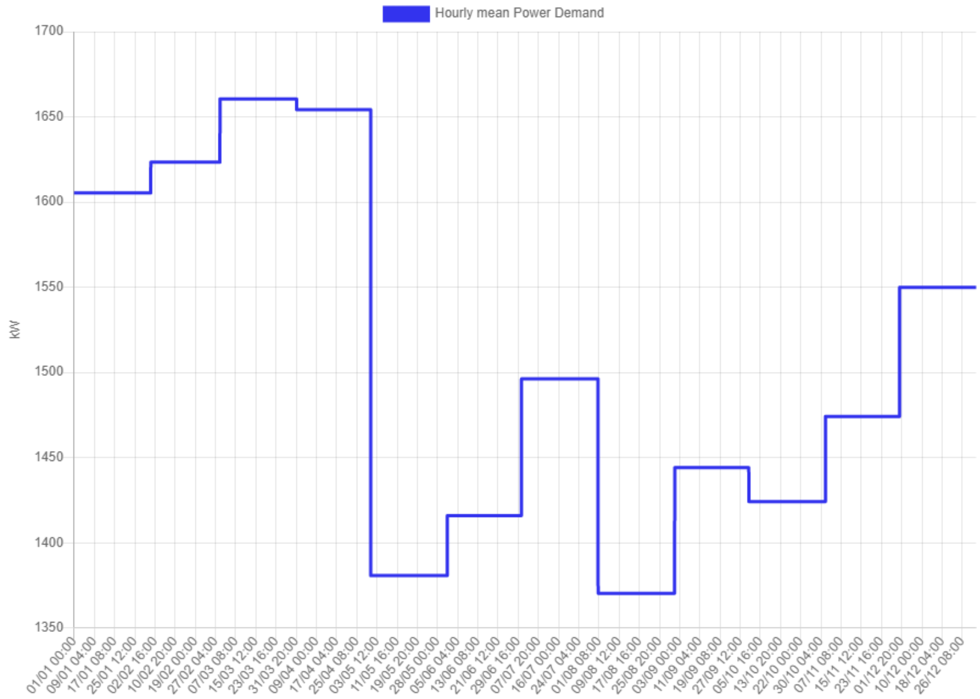

Figure 29: Modeling of Total Hourly Heat Demand

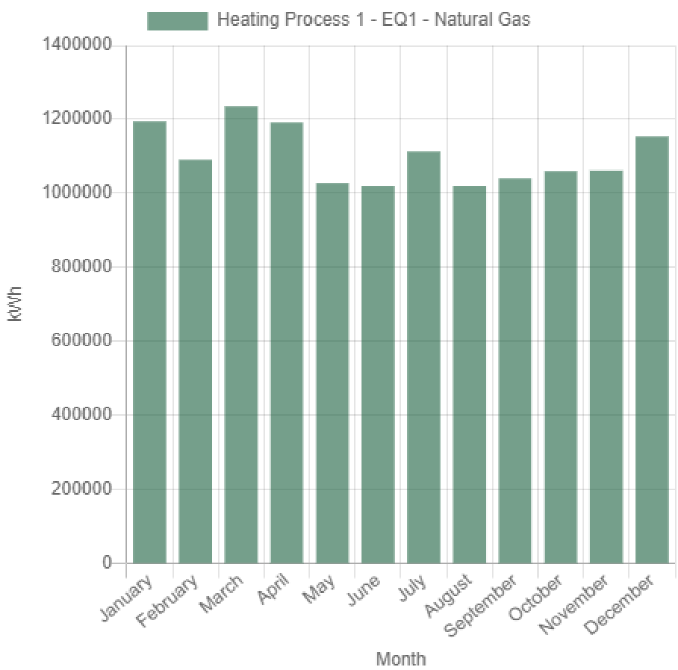

Figure 30: Modeling of Monthly Heat Demand and Breakdown among Processes

The Company has a free ground area of 26,245 m^2. No significant obstacles and sources of shading are present, neither significant space is required for other installations. Based on the preliminary information gathered, all the ground area is suitable for the installation of solar systems.

The monthly profiles of direct normal and global solar irradiance at the site are presented in Figure 31.

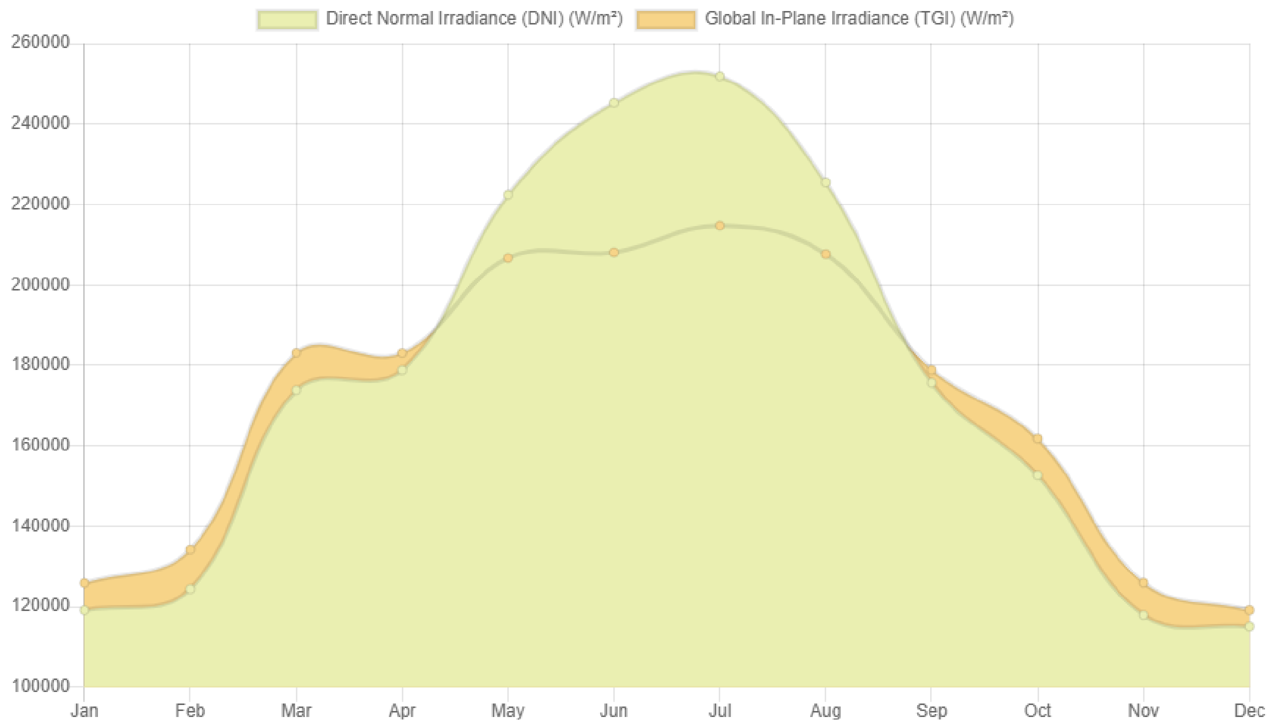

Figure 31: Direct Normal and Global In-Plane Solar Irradiance Monthly Profiles

The target plant requires for its processes heat in form of overheated steam at 195°C. Based on this range of operational temperatures, in line with the matching carried out in SHIP2FAIR D2.1, three technologies are identified as potentially most appropriate:

- Parabolic Trough Collectors (PTC)
- Linear Fresnel reflectors (LFR)
- Vacuum Flat Plate (HVFP)

Based on the algorithms implemented in the SHIP2FAIR replication tool the following maximum collector gross areas were determined to fit on the available ground area for the different technologies of solar collectors:

- 19,684 m^2 for LFR.
- 13,123 m^2 for PTC.
- 14,566 m^2 for HVFP.

The potential monthly thermal energy production of those solutions are compared with the monthly heating demand of the site in the chart in Figure 32.

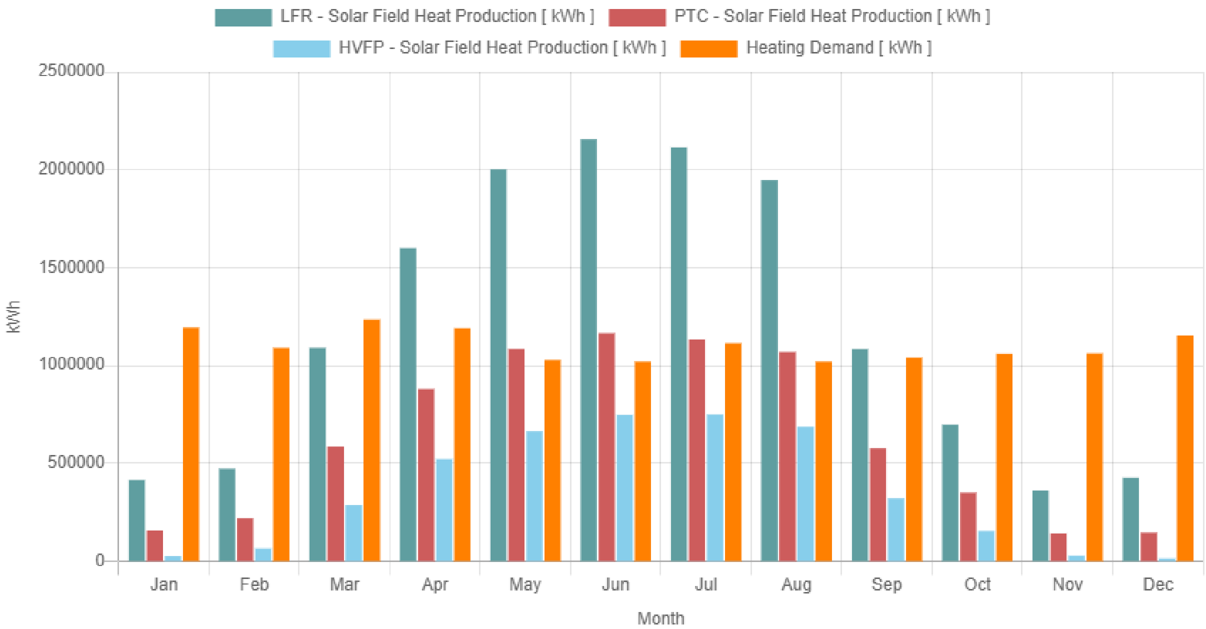

Figure 32: Comparison Monthly Heat Demand and Potential Solar Energy Input as Function of Technology and Storage Capacity

After having determined the potential solar heat production in the considered scenarios, the SHIP2FAIR replication tool starts carrying out a series of sensitivity analyses aimed at identifying the optimal size of the thermal energy storage required in combination with the collectors. The results of the optimization are:

- the Fresnel collector is clearly the favourable collector type and reaches the best results of the three technologies in all KPIs;
- based on the LCOH analysis, the optimal storage size is identified as of 10 MWh, which provides an LCOH of 109 €/MWh; with a significantly smaller storage capacity of 5 MWh the LCOH is 19% higher with 130 €/MWh;
- the solar share reaches up to 51.9 %; the smaller storage of 5 MWh reduces the solar share to 42.8 %;
- the Fresnel system reaches a payback of 20.8 years without consideration of funding;
- the emissions savings account to 30,613 tCO_2e over the lifetime (25 years).

3.10 Case Study 10 – Textile, India

The client is one of India's largest integrated textile and apparel companies, with a strong retail presence in the country and a pioneer of denim in India. The company's prime production facilities are located near Santej, Gandhinagar, although other production sites can be found in other Indian provinces.

The production site in Gandhinagar is used mainly for manufacturing cotton shirts, denim, knits, and advanced fabrics for its own, as well as global, brands. Although not the highest irradiation in the country, the location accounts for a significant direct normal solar irradiation, which is favourable for concentrating solar technologies.

The production plant operates several processes, running 24/7 and 360 days per year. The analysed processes work with saturated steam at 170 °C and a pressure of 7 bar. Currently, the main energy source is based on coal.

The monthly fuel consumption is entered as input in the replication tool; the sum of energy consumed in form of coals amounts to 614,371 MWh/y.

The trend of hourly and monthly heat demand modelled with the SHIP2FAIR tool is presented respectively in Figure 33 and Figure 34.

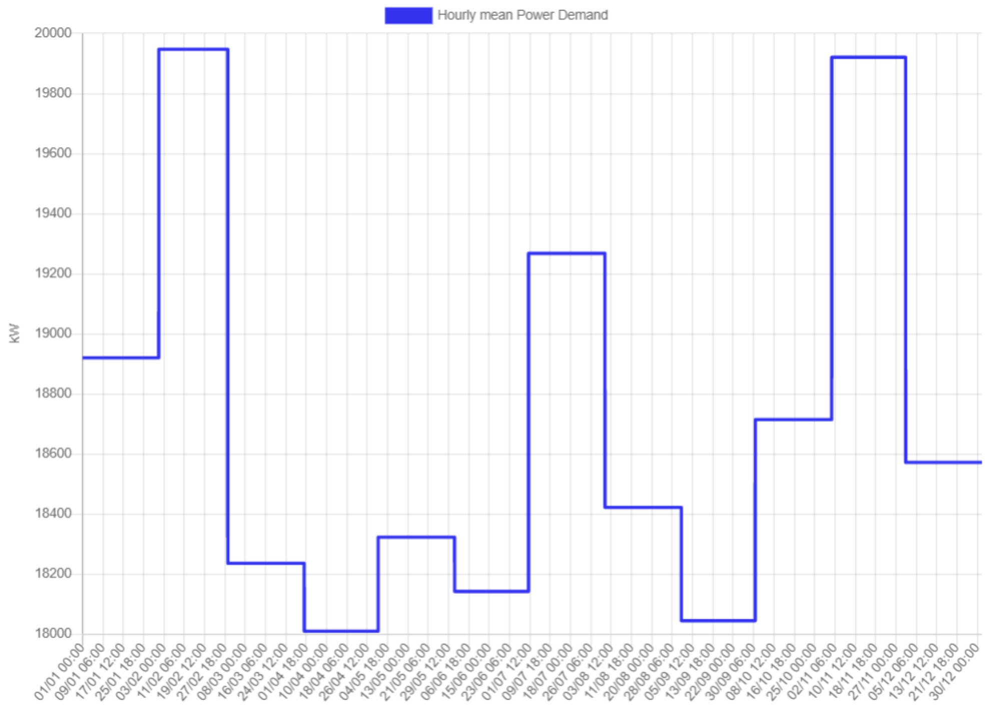

Figure 33: Modeling of Total Hourly Heat Demand

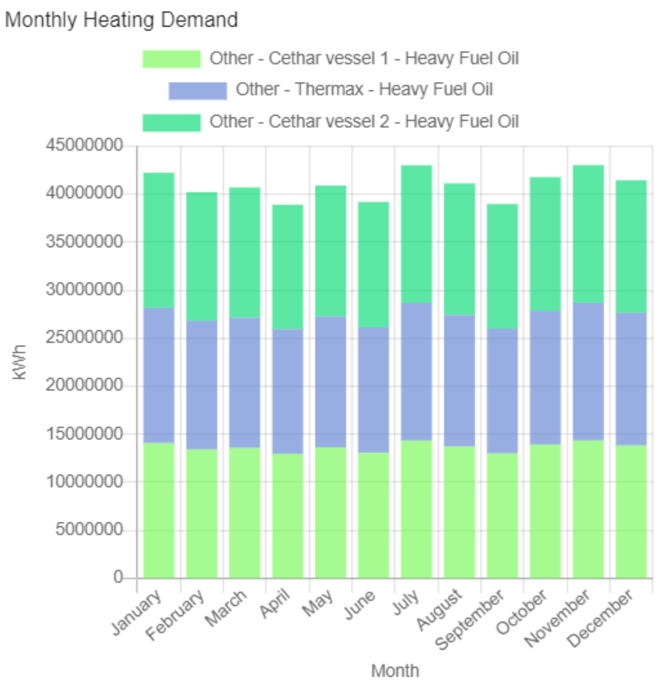

Figure 34: Modeling of Monthly Heat Demand and Breakdown among Processes

The client has a free ground area of 24,000 m^2. No significant obstacles and sources of shading are present, neither significant space is required for other installations. Based on the preliminary information gathered, all the ground area is suitable for the installation of solar systems.

The monthly profiles of direct normal and global solar irradiance at the site are presented in Figure 35.

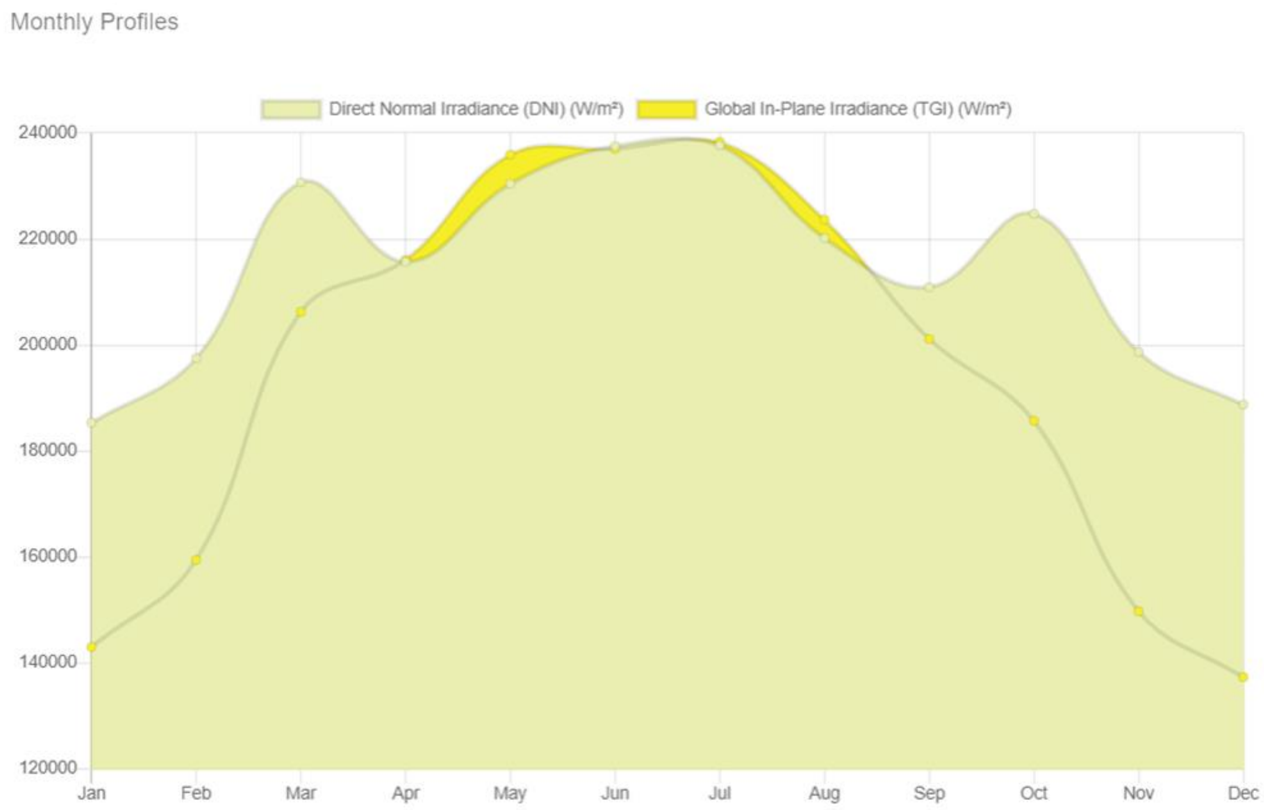

Figure 35: Direct Normal and Global In-Plane Solar Irradiance Monthly Profiles

The target plant requires for its processes heat in form of saturated steam at 170°C. Based on this range of operational temperatures, in line with the matching carried out in SHIP2FAIR D2.1, three technologies are identified as potentially most appropriate:

- Parabolic Trough Collectors (PTC);
- Linear Fresnel reflectors (LFR);
- Vacuum Flat Plate (HVFP).

Based on the algorithms implemented in the SHIP2FAIR replication tool the following maximum collector aperture areas were determined to fit on the available ground area for the different technologies of solar collectors:

- 11.400 m^2 for PTC.
- 17,100 m^2 for LFR.
- 12,654 m^2 for HVFP.

The potential monthly thermal energy production of those solutions are compared with the monthly heating demand of the site in the chart in Figure 36.

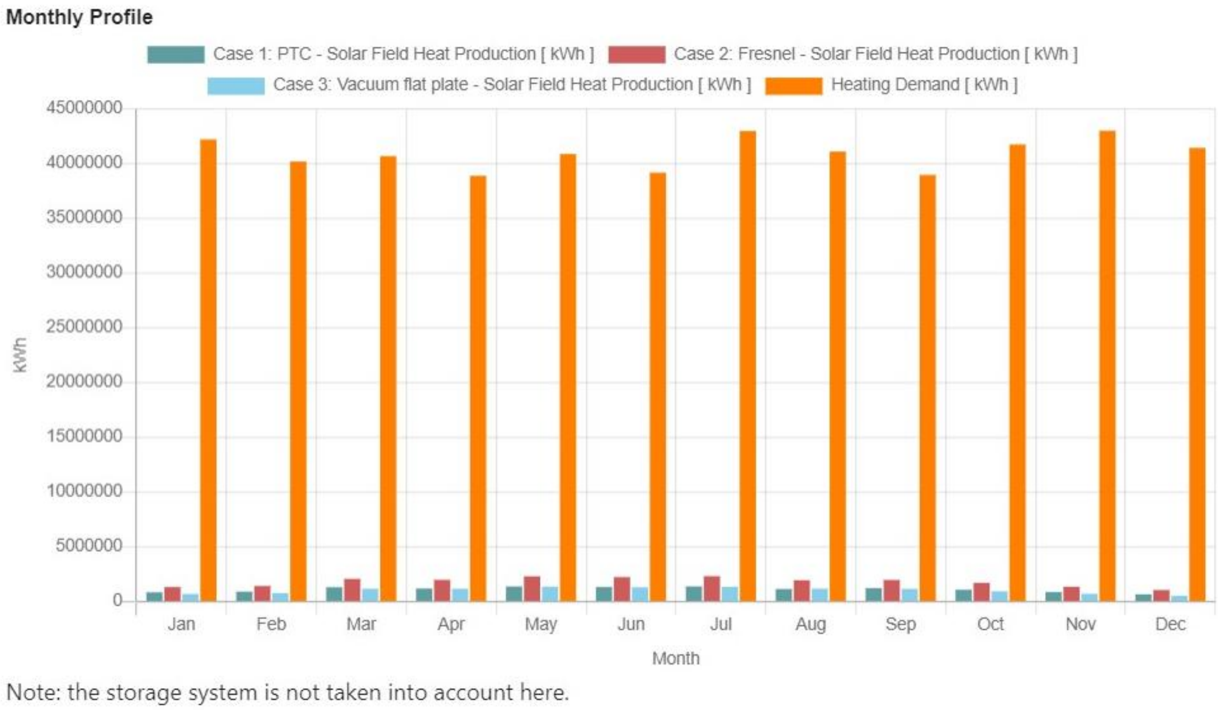

Figure 36: Comparison Monthly Heat Demand and Potential Solar Energy Input as Function of Technology and Storage Capacity

After having determined the potential solar heat production in the considered scenarios, the SHIP2FAIR replication tool starts carrying out a series of sensitivity analyses aimed at identifying the optimal size of the thermal energy storage required in combination with the collectors. The results of the optimization are:

- considering the process characteristics and results presented, the Fresnel collector is depicted as the preferred collector type and reaches the best results of the three technologies in all KPIs;
- based on the LCOH analysis, the optimal storage size is identified as the minimum for the collector system operation, but not needed for feeding the processes. This conclusion can be drawn due to the very high demand from the industrial plant in comparison to the sizes of the collector fields proposed within the available area. The lowest LCOH obtained was 16.85 €/MWh for the Fresnel technology, 23.9 €/MWh for parabolic through collector, and 25.4 €/MWh for the High-vacuum flat plate. Larger storages in this case can just make the project more expensive and is therefore not recommended;
- the solar share reaches up to 4,3% with the Fresnel collector technology and does not change in case of larger thermal storages;
- the Fresnel collector system reaches the lowest payback period of 8 years without consideration of funding. The PTC and High-vacuum flat plate cases reach 11.6 and 11.8 years respectively;
- the emissions savings for the Fresnel collector case account for 190,840 tCO_2e over the lifetime (25 years). For the High-vacuum flat plate and PTC cases, the savings amount to 112,424 and 108,309 tons respectively.

4 DISCUSSION OF RESULTS

The results of the replication studies presented in the previous chapter are summarized in Table 1, which presents for each of the ten studies:

- the temperature at which thermal energy is needed in the plant;
- the technology selected as best suitable;
- the area of the collectors to be installed;
- the resulting Levelized Cost of Heat;
- the resulting payback time;
- the share of thermal demand that can be covered by solar source;
- the avoided GHG emissions thanks to the solar thermal system.

Table 1 – Summary of Replication Studies' Results

	Thermal Demand Temperature	**Best Technology Selected**	**Collectors Area**	**LCOH**	**Payback Time**	**Solar Share**	**GHG Emissions Avoided**
	°C	-	*m²*	*EUR/ MWh*	*y*	*%*	*tCO_2e/y*
Case Study 1 – Textile, Italy	50-70	FPC	827	76.4	18.5	2.3	68
Case Study 2 – Chemical, Slovenia	130-180	LFR	25,981	44.9	11.0	6.0	2,315
Case Study 3 – Office/Laboratory, Italy	90-160	LFR	180	49.8	12.1	2.0	434
Case Study 4 – Waste Treatment, France	57-90	HVFPC	190	75.3	25.0	40.0	800
Case Study 5 – Dairy, Spain	85	HVFPC	1,665	17.5	3.4	78.7	301
Case Study 6 – Meat Processing, France	55-96	HVFPC	2,200	44.0	12.0	18	520
Case Study 7 – Brewery, Spain	35-100	HVFPC	6,577	34.7	5.6	7.2	1,240
Case Study 8 – Food, Jordan	175	LFR	2,216	51.0	4.4	80.9	581
Case Study 9 – Chemical, Spain	195	LFR	19,684	109.0	20.2	51.9	1,224
Case Study 10 – Textile, India	170	LFR	17,100	16.8	8.0	4.3	7,633

It can be noticed that High Vacuum Flat Plate Collectors (HVFP) and Linear Fresnel Reflectors (LFR) are recurring as most suitable technologies in most of the case studies. Respectively, HVFP result the most suitable technology for the considered industrial sites having a thermal demand at a temperature slightly below 100°C, generally in form of hot water, whereas LFR are the most suitable technology in those having a thermal demand between 100 and 200°C, generally in form of steam.

It can also be highlighted that in most cases the availability of spaces for the installation of solar thermal collectors is the limiting factor: for this reason, several of the industrial sites subject of a replication study are able to satisfy only a limited share (below 10%) of the total heat demand with solar thermal. Nevertheless, there are a few sites having a considerable amount of space available, even on land plots close to the industrial complex, which for this reason are able to reach very high solar shares over the total heat demand, between 50 and 80%. The quantification of the avoided GHG emissions is strongly correlated with the solar share as well as with the total thermal energy demand of the site, which influences the absolute amount of GHG emissions avoided; this is also influenced by the fuel used to cover such energy demand in the baseline situation, which is natural gas in practically all cases except for the last industrial site, in India, which uses coal.

Under the financial perspective, the LCOH varies over a quite wide range as a result of different factors, among which the main one is the ratio between the initial investment for the installation of the solar thermal plant (including storage) and the thermal energy production of the site during the year and more in general during its useful life. The second financial parameter included in the analysis is the payback time for the investment, which in addition to the parameters described for LCOH also depends on the baseline thermal energy production cost, which in turn depends on the type and price of fuel used and on boilers efficiency. Considering the dependence of the financial profitability of the investment on the price of fuel in the baseline situation, it is worth highlighting that all the replication studies have been carried out considering “normal” fuel prices, i.e. those before the energy crisis arising from 2022 geopolitical situation; considering 2022 energy prices, a much better financial performance of the investment would be achieved.

Based on the results presented above, it can be concluded that solar thermal technologies have a good potential for implementation in all industrial sectors characterized by a considerable thermal energy demand. A suitable technological solution can be identified for several industrial sectors, provided that the site-specific pre-requisites are met especially in terms of solar resource availability (depending on latitude and on local conditions like orientation/slope/obstacles) and of space availability for the installation of solar thermal collectors. The financial return on investment is still relatively low but it can be substantially increased in case fuel prices on the market are increasing (like in 2022) or in case public incentives are available to support the decarbonization effect of the installation of solar thermal systems in industrial sites.

5 CONCLUSIONS

The present SHIP2FAIR D8.4 focuses on replication studies executed making use of the SHIP2FAIR Replication Tool with the intention of demonstrating the technological viability, maturity, and affordability of solar heat technology for industrial processes. These studies are related to 10 sites in 6 different countries (Italy, Spain, France, Slovenia, Jordan, India), representing 8 different industrial sectors (textile, chemical, wastewater treatment, dairy, meat processing, brewery, food, and research laboratory).

The current public deliverable only displays the key findings of the replication studies in anonymized form due to the sensitive nature of the data on which they are based (company location, layout, process flow diagram, energy usage and production values). The complete replication studies are being delivered to the European Commission separately from this main report, of which they constitute confidential Appendices.

Besides the site-specific results, more general conclusions can be drawn: solar thermal technologies have a good potential for being adopted by all industries with significant heat demand. This is applicable especially when site-specific prerequisites are satisfied, particularly in terms of solar resource availability (depending on latitude and local conditions like orientation/slope/obstacles) and of space availability for the installation of solar thermal collectors, identifying the most suitable technology based on thermal energy demand and resource availability. Although the financial return on investment is still quite low for these solutions, it may increase significantly if public incentives are made available to support the decarbonization effect of the installation of solar thermal systems in industrial sites or if market fuel prices rise (as they did in 2022). Based on the studies carried out, the Levelized Cost of Heat varies between 17 and 109 €/MWh and the payback time between 3 and 20 years. HVFP collectors showed the best performance and economical KPIs in all case studies for process temperatures below 100 °C and water as heat transfer fluid, while Fresnel technology resulted as best suitable technology for case studies with temperatures above 100 °C.

6 PENETRATION OF SOLAR THERMAL ENERGY IN THE SPANISH AGRO-INDUSTRY: THE CASE OF AGRI-FOOD COOPERATIVES

As a complement to the pre-feasibility studies, given that one of the partners involved, Cooperativas Agro-alimentarias de España, represents a large group of agri-food industries, potential practitioners who can use solar thermal installations, in the final phase of the project it is proposed to carry out a diagnosis of the penetration that solar thermal has had in the years of development of the project in these industries, comparing it, in turn, with the integration of other renewables and evaluating future prospects for the implementation of solar thermal in the Spanish food industry.

A sample of 130 agri-food cooperatives was selected, covering a wide range of sizes in terms of energy consumption - from 3 to 71,000 MWh per year (average 600 MWh) - but also representing practically all Spanish regions and agri-food sectors. Analysis of the results revealed some interesting data:

- Almost 20% indicate that their energy supplier has a green energy certificate (100% of the energy supplied is of renewable origin);
- 55% of the responding cooperatives claim to have a renewable energy installation;
- The majority of respondents have a renewable energy supply that covers between 20% and 40% of their needs;
- A small number of cooperatives have integrated solar thermal energy into their processes, after photovoltaic energy - the most common, used by 72% - and the use and production of biomass.

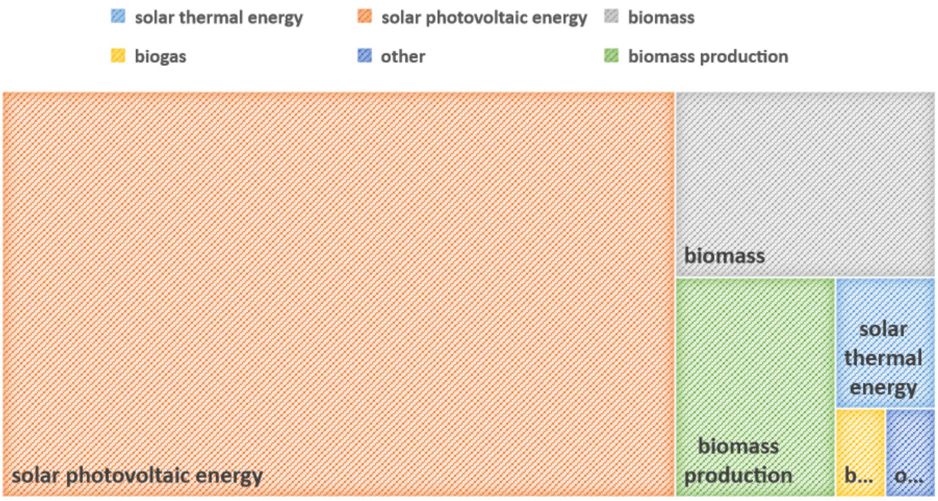

Figure 37: Declared renewable energy installations.

The following data on installed solar thermal capacity was obtained:

- Total installed capacity: 28 kW on average;
- Annual production: 29,025 kWh on average;
- Ownership of the plants: own;
- Uses: drying, cooling, hot water, sterilisation, pre-heating;
- Average temperature obtained: 90°C;
- Location: on the roof;
- Area used: 100 m2 on average;
- Technology: flat-plate collector.

In the near future, 66% intend to expand their capacity or use other renewable technologies in the next 0-3 years, 81% of which are solar PV and 11% solar thermal, ahead of the 5% that intend to switch to biogas.

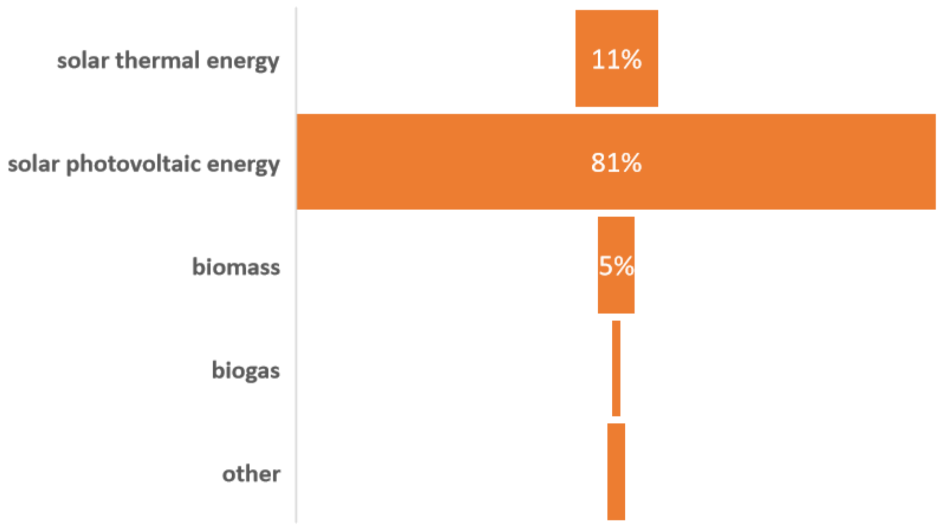

Figure 38: Intention in 0-3 yerars to install renewables.

According to this analysis, the interest of the agri-food cooperatives in renewable energies has been noted, with an exponential growth in the number of installations in recent years, but also in solar thermal installations, where there is a growing intention for the future. The current system of the cooperatives includes the use of renewable energies for their own consumption, with their own installations on their roofs.