13. INTEGRATION OF SOLAR THERMAL TOGETHER WITH HEAT PUMPS

13.1 Overview of integration strategies

13.1.1 Practical considerations

A Solar Thermal (ST) system converts solar energy into heat by absorbing solar irradiance and using a heat transfer medium that supplies heat into an application (heat consumption).

In this regards, solar heat is subject to certain limitations:

- Solar energy is intermittent in nature and as a result heat produced by any ST system fluctuates significantly throughout the day and year (the profile of the solar heat supply is bell-shaped). Typically, in European climates, a ST system delivers a significantly lower quantity of heat during the winter period than in the summer season. In addition, if desired, summer operation may shift to much higher temperatures.
- For a given level of solar irradiance, the solar-to-heat energy conversion efficiency of a ST system is reduced as the operating temperature is increased. That means, that a ST system delivering heat at 100 °C is more efficient than the same system supplying heat at 150 °C.

To compensate the above limitations, short-term thermal energy storage (TES) is used to smooth intra-day variations, extend the operating hours of the system (e.g. overnight), store heat in periods with no demand (e.g. weekends), and in general to increase the flexibility of heat supply.

In this context, the SPIRIT project will assess the feasibility of using solar heat as a heat source for the operation of HTHPs in industrial applications under various operating scenarios with or without the presence of waste heat streams.

For the purposes of the project, a top performing non-concentrated solar thermal technology will be used. This is the High Vacuum Flat Panel (HVFP) technology, that has been developed, patented, manufactured and marketed by TVP Solar SA (a Swiss-based SME and SPIRIT partner).

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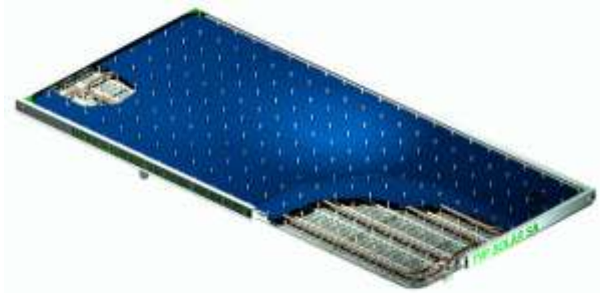
TVP's High Vacuum Flat Panel (HVFP) non-concentrated solar thermal technology

TVP produces its MT-Power HVFP, in its ISO 9001-certified manufacturing facility in Avellino, Italy. MT-Power is a high-vacuum solar thermal flat plate collector certified under the Solar Keymark EN ISO 9806:2013[1].



The novelty of HVFPs rely on TVP patented high vacuum insulation technology, which allows the panel envelope to hold < 10^{-3}mbar internal pressure while withstanding 10 ton/m^2 atmospheric pressure. TVP high vacuum insulation suppresses thermal losses from convection within the panel envelope, distinctively contributing to the certified MT-Power sun-to-thermal performance up to 200°C.

The panel is made of materials qualified for long-lasting high-vacuum operation (20+ years), corrosion-proof all-metal casing, and embeds a patented auto-regenerative getter pump, which collectively preserves high vacuum integrity for at least 20 years. Thus high-vacuum integrity is what secures MT solar-to-heat certified efficiency and prevents any performance degradation throughout the product lifetime.

The diagram below depicts a generic layout of a typical solar thermal system:

- The ST panels are arranged in strings (mono-layer or multilayer) that are connected in parallel with each other in a way to fit to the available space and meet the operating requirements of the system.
- Cold pressurized water[2] enters the panels (blue line) and is heated as it circulates within the strings.
- Then, the hot water passes through a heat exchanger (HX) to transfer heat to the application (e.g. an industrial process, a HTHP, the return condensate or a boiler's feedwater, etc.).
- A dry cooler is also part of the system to dissipate excess solar heat in case there is not (enough) demand and the TES tank is already fully loaded.

[1] Solarkeymark datasheets of all certified panels: http://www.solarkeymark.nl/DBF
[2] Other Heat Transfer Fluids may be used including water-glycol or thermal oil.

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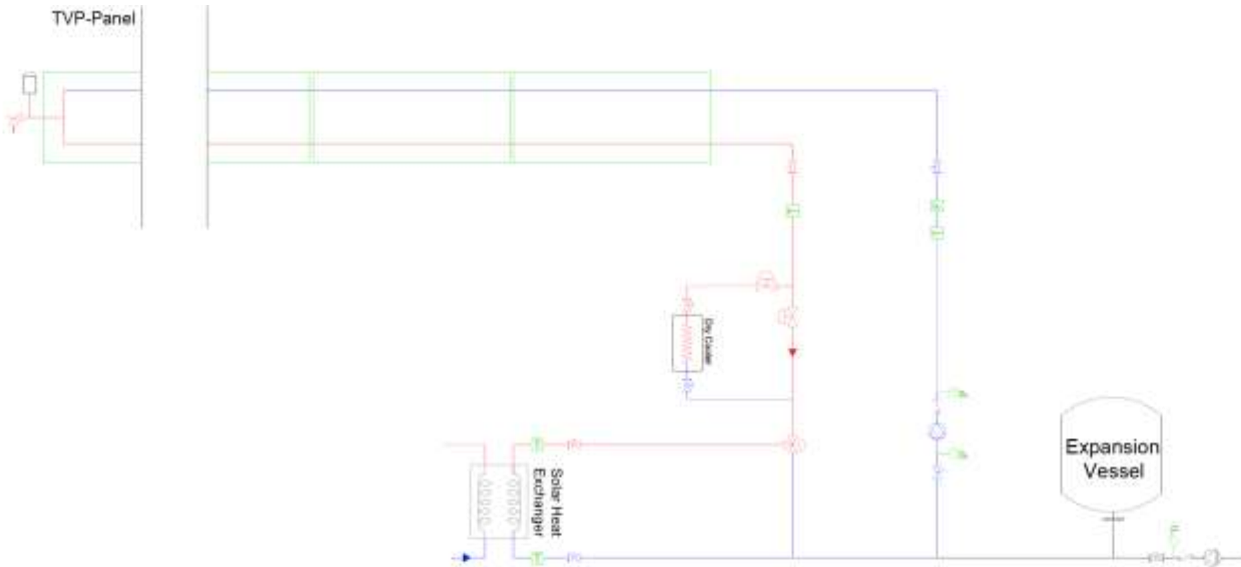

Figure 36: Operating principles of HVFP-based solar thermal (ST) systems

Operating principles of HVFP-based solar thermal (ST) systems

The operation of the HVFP ST system is fully automated and goes as follows:

i. Operation begins as soon as solar irradiance reaches a minimum threshold. At that moment the control system drives the inverter for the system pump to circulate the HTF (Heat Transfer Fluid). The pump flow rate is variable to achieve and maintain the system target operating temperature. The HTF is circulated in the system until the target temperature is achieved.

ii. Once the temperature is in the range of acceptance, a valve is open and the heat starts to be transferred to the application (e.g. HTHP);

iii. The system is equipped with a dry cooler to avoid overheating. It is in parallel with the system and connected to it via 2-way valves. If the temperature in the system goes above a threshold the control system modulates the valves to discharge the excess heat.

iv. During normal operation of the system, the pump is actuated via PLC using live information from the sensors, including the weather station, the flow meters, and the temperature sensors. In the case of extreme need, an emergency shut-off button can be activated.

v. In the case of electricity failure (e,g, blackout) the system will not be able to operate electrical-driven pumps and control system unless a UPS unit is installed. When the electricity resumes, the PLC will reset, and the system will re-engage. Following a blackout, the PLC must be checked to verify that proper system operation has begun, and verify no alarms are activated.

vi. The system performance and information can be accessed by operators in real-time via the dedicated webpage.

Sizing and design configuration of the HVFP-based ST systems
In most industrial applications, the size of the ST field is limited by the availability of suitable space (on the ground or roof) for the installation of the panels, and not by the expected heat demand. As a rule of thumb, **1 MWth peak power** corresponds to around 1600 m^2 of panels that require an area of around 3000 m^2 to be installed (a minimum distance is required between the strings of the panels to avoid shading effects).

To pre-assess the feasibility of applying a ST system, a quick Go/No-go decision-making process can be followed as proposed below:

Step 1: The following basic information is initially collected:
- Location of the site; Solar irradiance preferably: Global Horizontal Irradiance (GHI) ≥ 1'100 $kWh/m^2/year$
- Space availability (rooftop or on the ground); Should preferably be ≥3000 m^2 of single space
- Heat demand capacity (MW) and process temperatures (inlet / outlet); Should preferably be: ≥ 1 MW of capacity and T ≤ 150°C
- Heat demand profile; Should typically be: ≥ 8 Hrs/Day; ≥ 5 Days/Week & ≥ 250 Days/Year. Seasonal variations of demand (low and high)
- Actual unit cost of fossil fuel used for heat generation

Step 2: Based on the above information and the diagram Figure 37 and Table 12 below, the thermal energy generated by the HVFP-based ST field is roughly estimated. The size of the solar field is calculated based on the abovementioned rule of thumb

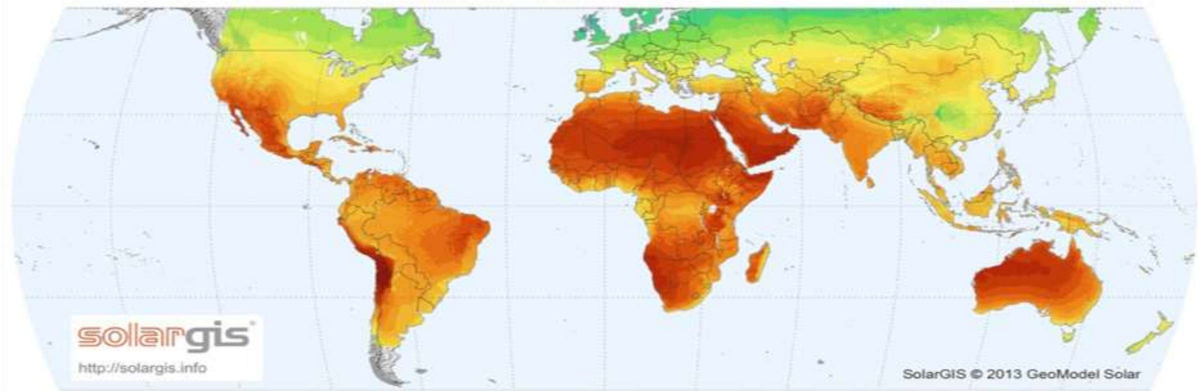

Figure 37: Global Horizontal irradiation

Table 12: Energy yield and CO2 emission avoided by HVFP-based solar thermal

Producing > 1 MWh_t/m^2 per year								
IRRADIANCE		1.100	1.300	1.500	1.700	1.900	2.100	$MWh/m^2/y$
$Tm=(T_{in}+T_{out})/2$		TVP Energy Yield						
Tm	@60 C	0.733	0.938	1.143	1.289	1.406	1.582	$MWh/m^2/y$
Tm	@95 C	0.682	0.791	0.967	1.113	1.231	1.406	$MWh/m^2/y$
Tm	@120 C		0.750	0.850	0.967	1.084	1.260	$MWh/m^2/y$
Tm	@150 C				0.791	908	1.084	$MWh/m^2/y$

Cutting > 6 ton/m^2 of CO_2 opl								
IRRADIANCE		1.100	1.300	1.500	1.700	1.900	2.100	$MWh/m^2/y$
$Tm=(T_{in}+T_{out})/2$		TVP Avoided CO_2 emissions						
Tm	@60 C	4.75	6.08	7.41	8.36	9.12	10.26	ton/m^2 opl
Tm	@95 C	4.42	5.13	6.27	7.22	7.98	9.11	ton/m^2 opl
Tm	@120 C		4.86	5.52	6.27	7.10	8.18	ton/m^2 opl
Tm	@150 C				5.12	5.89	7.03	ton/m^2 opl

STEP 3: The cost of solar heat is roughly calculated based on the following indicator: Rough annual unit cost of the solar system: 28 €/m^2/year (this applies for MW-sized systems). Note: for simplicity reasons the operating cost for the solar field is considered negligible.

Note: in calculating the cost of solar heat the following cost items are not taken into consideration at this stage of pre-assessment: cost of preconstruction works, cost of integration, cost of thermal storage, other case-specific costs, and the cost of capital.

Step 4: The user can compare the unit cost of solar heat roughly calculated in the previous step with the actual and expected unit cost of heat generation at their site. If the former is lower, then they may move forward to a more detailed feasibility analysis. To calculate the existing cost of heat typically the cost of natural gas (or any other fossil fuel they use) is divided with the overall efficiency of the heat generation system (e.g. boiler; typically an efficiency of 80 %- 85 % is taken into consideration). The availability of subsidies, grants or other financial incentives supporting the installation

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of renewable heating solutions may also be explored at this stage as well. The same applies for the cost of CO_2 emissions.

Assuming a positive outcome of the above preassessment, a more detailed feasibility analysis can be made, including detailed energetic simulations, preliminary design layouts of the solar thermal system, sizing of the thermal storage, etc.

The above applies for any industrial application of the HVFP-based systems. In the case of ST integration with HTHP and waste heat, the relevant calculations become more complex. This is because the addition of a HTHP may affect the operating temperatures of the ST system, as well as its sizing and the size of the TES tank.

As an example, the Table 13 and diagram Figure 38 below indicate how the solar heat generation may be affected in relation to operating temperature. The calculations have been made for 5 distinct levels of solar irradiance ranging from as low as GHI[3]=1'100 kWh/m²/year (e.g. Munich) to as high as 1'900 kWh/m²/year.

Table 13: Solar heat production [in kWh/m2/y, and normalized on a 100% basis operation at 60 °C] for different operating temperatures and locations

GHI Operating T	1100 kWh/m2/y	1300 kWh/m2/y	1500 kWh/m2/y	1700 kWh/m2/y	1900 kWh/m2/y
@60 °C	0,733	0,938	1,143	1,289	1,406
@95 °C	0,682	0,791	0,967	1,113	1,231
@120 C		0,750	0,850	0,967	1,084
@150 C				0,791	0,908
GHI **Operating T**	**1100 kWh/m2/y**	**1300 kWh/m2/y**	**1500 kWh/m2/y**	**1700 kWh/m2/y**	**1900 kWh/m2/y**
@60 °C	100	100	100	100	100
@95 °C	93	84	85	86	88
@120 C		80	74	75	77
@150 C				61	65

[3] Global Horizontal Irradiance

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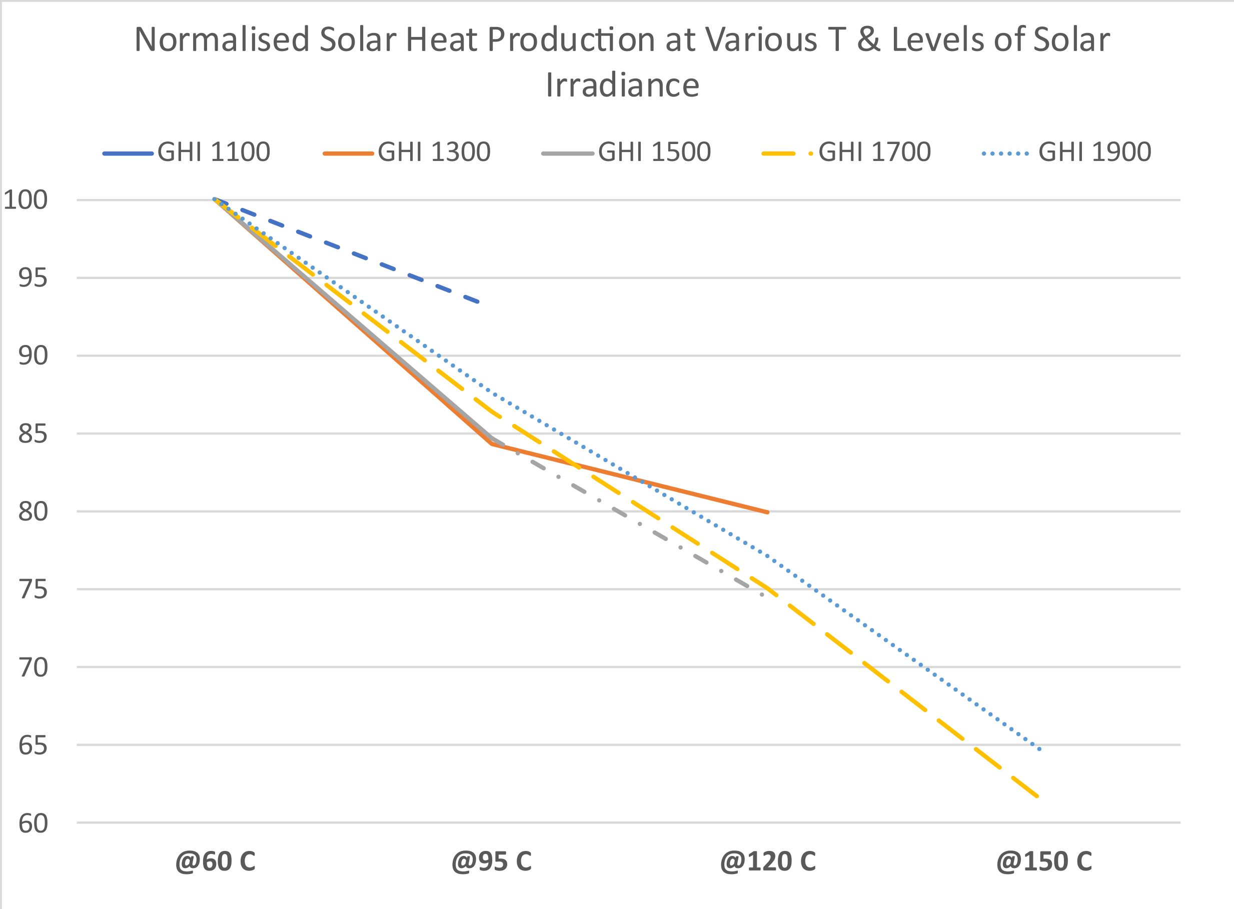

Figure 38: Normalized solar heat production at various T & levels of solar irradiance

The above figure Figure 38 show that in low irradiance locations, the solar-to-heat conversion efficiency may drop by 15 pp[4] when moving from a low operating temperature of 60 °C to a higher one of 95 °C. In relatively high irradiance places in Europe, increasing the temperature from 60 °C to 120 °C has a similar effect of 25 pp drop.

This dependence on the operating temperature is also influenced by other parameters such as the ΔT (Tout-Tin). In any case, it should be taken into consideration during the analysis of specific solar thermal to HTHP integration scenarios, because the HP efficiency depends also on the ΔT between heat source and heat sink.

[4] Percentage points

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13.1.2 Possible integration strategies

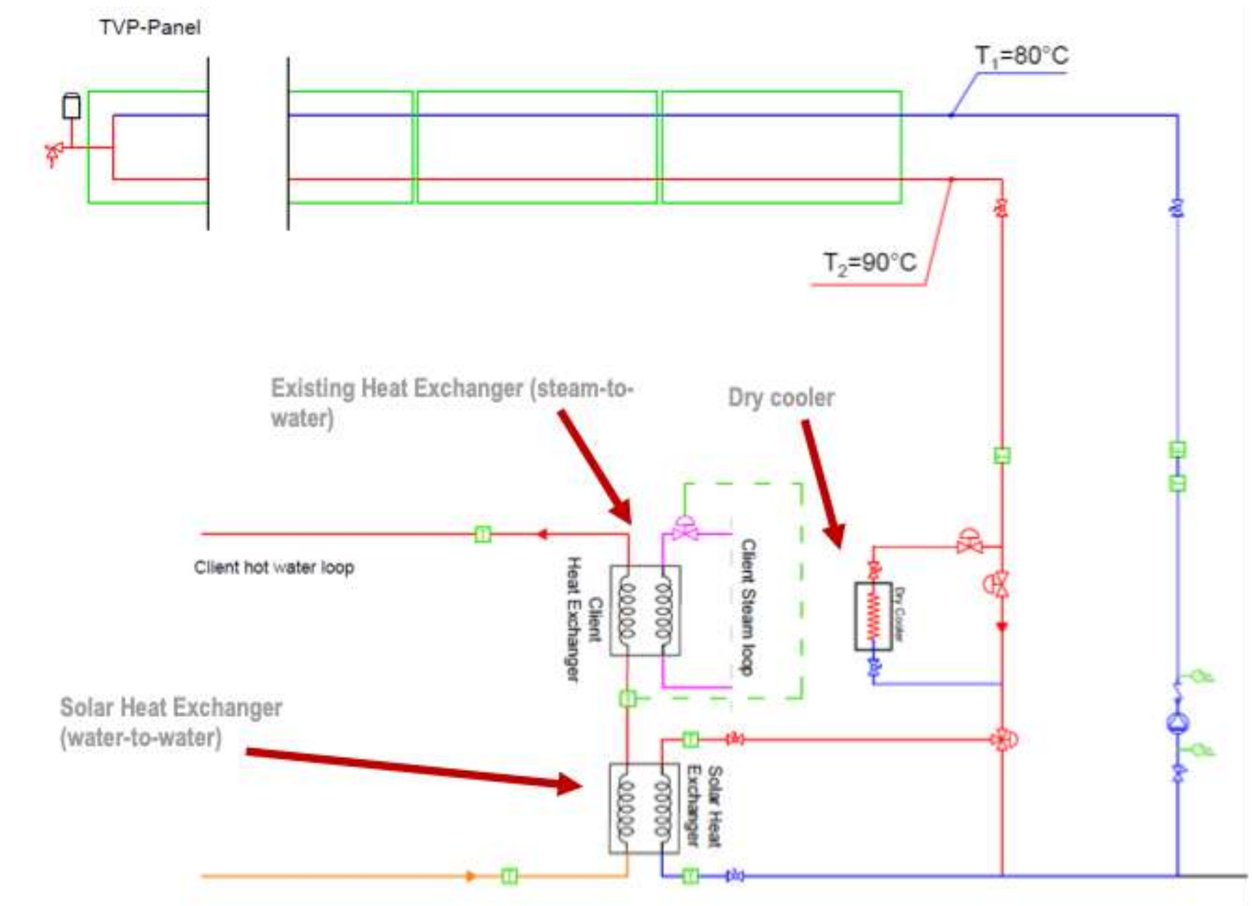
In general, the ST system can provide a complementary heat source to the HP in cases where the waste heat streams are not sufficient in terms of quantity or temperature level. Under certain, conditions, during the high irradiance hours in summer time, it may even temporarily substitute a HTHP. Coupling with a TES solution may be needed to enhance flexibility during low-irradiance hours or to optimize supply and demand management, as well as to provide the heat source during extended hours.

Therefore, an integrated ST + TES + HP (STTESHP) solution may be used to serve the following scenarios:

- Solar heat to complement and/or provide *100% of* the heat source for the HTHP operation
- HTHPs used to upgrade solar heat during the winter (low irradiance) period. Solar thermal (ST) systems may provide heat directly to the process during the summer period, when it can operate efficiently at significant higher temperatures.
- HTHPs used to upgrade solar heat during low-irradiance hours
- HTHPs used to upgrade stored solar heat outside the operating hours of the ST system.
- Solar heat and waste heat used in combination as a heat source to HTHPs (also, solar heat may increase the temperature of the waste heat and thus allow the HP to operate at a lower ΔT).

The configuration and operational objectives of a STTESHP solution depend also on the integration point of the demand side (industrial consumer). Central integration (typically integration to a steam network or integration to preheat the return condensate) or direct process integration (i.e. integration to meet the heat demand of a specific industrial process or set of processes). In the case of the integration with the steam network, much higher temperatures may be required. As a result, solar heat tends to provide the heat source throughout the year, while no significant changes in the thermal network are needed. In the other cases (preheating condensate, direct process integration) solar heat may cover the demand side during high irradiance periods. However, in the case of direct process integration a secondary hot water circuit is needed to connect the ST system with the application side.

On top of hot water generation, TVP's ST systems can operate in dual mode: (i) generating hot water during the winter period; and (ii) generating low pressure steam during the summer period. This may also influence the operating scenarios. In this case, MVR may be applied to increase the pressure of the solar steam. However, such a scenario is considered outside the scope of this report.



Note: TES is considered necessary for flexibility and/or extended hours operation purposes. Sizing depends on the purpose it may serve (relatively small buffer tank for minor intra-day adjustments; storage tank for intraday variations; larger storage tank for extended hours operation overnight; large storage tank for storing heat during weekend shutdown).

The Table 14 summarises indicative operating configurations of an integrated Solar Thermal (ST), a Thermal Energy Storage (TES) solution, and a High Temperature Heat Pump (HTHP). From the ST perspective, such configurations depend heavily on the location (i.e. on the level of solar irradiance).

Table 14: Combined operating configurations of ST+TES+HTHP

	Winter Operation		Summer Operation	
ST-TES-HP	Heat Source:	ST: 80 °C - 100 °C	ST: 100-160C	
	Heat Sink:	120 °C - 140 °C	140 °C - 200 °C	Solar heat for process heat up to 150 °C Or HP for process heat > 120 °C
	TES	Non-pressurised water	Pressurised or non-pressurised water	Pressurised water up to 140 °C (to store solar heat)

13.1.3 Sizing considerations

In most cases, the size of the ST system is limited by the availability of suitable space (rooftop - load bearing >70 kg/m^2 - 80 kg/m^2) or on the ground in the vicinity of the location of heat demand (typically < 500 m from the solar field). As a result, the solar field is sized below the optimal point.

However, in the case of practically unlimited availability of suitable space, the optimal sizing of the ST system depends on the following main rules:

Heat demand profile during the high irradiance (summer) season: At that time, the ST operates at (near) maximum yield. Any excess solar heat that cannot be stored and consumed in the short-term (e.g. within a few days max) will be wasted. Wasted solar heat is equivalent to a proportional increase of the unit cost of heat. Furthermore, in order to dissipate the excess heat into the environment the dry cooler will consume electricity and thus increase the OPEX of the ST system.

- Integration options: Integration of solar heat at process level (and not e.g. at centralized steam network) typically allows the operation of the ST system at lower temperatures and thus at higher efficiency (= lower cost of solar heat).

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- Thermal storage capacity: Available TES solutions not only allow the overall system to respond to intra-day variations of heat demand, it also enables the operation during extended hours (e.g. in the case of industries operating 24/7), as well as to store excess heat during shutdowns of the industrial processes (e.g. during weekends, maintenance, etc.).

On this basis, the operating temperatures of the ST system are set (they may change from winter to summer and/or from low to high irradiance days) and the size of the solar field is defined so as to cover the demand during the summer season. As a next step, the ST system is modelled and detailed energetic simulations are performed (i.e. calculating the solar heat delivered on an hourly basis) aiming at optimizing operation. Such optimisations may target to: minimize unit cost of solar heat; minimize the unit cost of heat (taking also into consideration the cost of CO_2 emissions; maximise the share of solar heat; or maximise the CO_2 emissions reduction.

13.2 Demonstration cases

This section presents the results of simulations on solar heat generation potential for each of the three demo sites of the SPIRIT project and for three different scenarios corresponding to increasing amounts of installed area. Simulations have been performed using the TRNSYS software.

The following assumptions have been made:

The solar thermal system is using the High Vacuum Flat Plate (HVFP) collector technology of TVP Solar. Collector performance is calculated based on the SolarKeyMark Certificate datasheet of the MT-Power panel[5].

- A size of roughly 1 MW (between 1'500 m² and 1'600 m² of panels) is considered for all cases.
- Three scenarios have been calculated per pilot case based on three operating temperatures for the solar thermal system. One relatively low temperature (for all year operation), one higher (for summer operation) and one with Low-pressure steam.

[5] The datasheet can be found here: https://solarkeymark.eu/database/

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- For simplicity reasons, no thermal storage solution has been considered (to add flexibility and better match heat supply with demand)

Table 15 summarises the key input and output parameters for the energetic simulations for all three sites:

Table 15: Input and Output parameters for the simulation of each case

		Stella Polaris (Norway)	Smurfit Westrock (Czech Republic)	Tiense Suiker (Belgium)
City		Finnsnes	Hradec nad Moravic	Tienen
GHI[6] [kWh/m2/year]		752	1’111	1’060
Heat Transfer Fluid		Water	Water	Water
Panels’ Tilt Angle		35º	35º	35º
Scenario 1	Application Tin [° C]	18	70	76
	Application Tout [° C]	48	90	86
	Solar Field Peak Power [kW]	1’052	1’047	1’051
	Gross Area [m2]	1’472	1’560	1’568
	Installed Area [m2]	2’650	2’808	2’822
	Nr of panels	736	780	784
	SF Yearly Thermal Production [kWh/m2/year]	564	607	564
	SF Average Yearly Efficiency	58%	47%	46%
	Thermal Energy Delivered [kWh/year]	818’496	925’706	856’051
Scenario 2	Application Tin [° C]	18	120	76
	Application Tout [° C]	58	130	96
	Solar Field Peak Power [kW]	1’076	1’078	1’053
	Gross Area [m2]	1’512	1’780	1586

[6] Global Horizontal Irradiance

	Installed Area [m2]	2'722	3'204	2855
	Nr of panels	756	890	793
	SF Yearly Thermal Production [kWh/m2/year]	549	418	545
	SF Average Yearly Efficiency	57%	32	44
	Thermal Energy Delivered [kWh/year]	816'873	714'769	842'660
Scenario 3	Application Tin [° C]	83	-	-
	Application Tout [° C]	93	-	-
	Solar Field Peak Power [kW]		-	-
	Gross Area [m2]	1'638	-	-
	Installed Area [m2]	2'948	-	-
	Nr of panels	819	-	-
	SF Yearly Thermal Production [kWh/m2/year]	388	-	-
	SF Average Yearly Efficiency	40%	-	-
	Thermal Energy Delivered [kWh/year]	609'361	-	-

13.2.1 Stella Polaris (Norway): Solar heat generation potential and suitability

The site of Stella Polaris is located in one of Europe's outermost regions in the very north of Norway. As a result, it receives one of the lowest levels of solar irradiance. Furthermore, almost 96 % of the total annual solar irradiance is concentrated in the period from March to September (i.t. 7 months). This means that any solar thermal can only provide heat during this period. For instance, to serve industrial processes with corresponding high seasonality.

In this context, three scenarios have been considered: one (**SC1**) for operation at the lowest possible usable temperature (the solar thermal system will operate from 23 °C (Tin) to 53 °C (Tout)[7]), a second (**SC2**) to serve slightly higher temperature requirements (23 °C to 63 °C) and the third **(SC3)** close to 90° C (83 °C – 93 °C).

The paragraphs below provide an overview of the capacity of TVP's High Vacuum Flat Panel (HVFP) technology to deliver heat for each of the above mentioned scenarios:

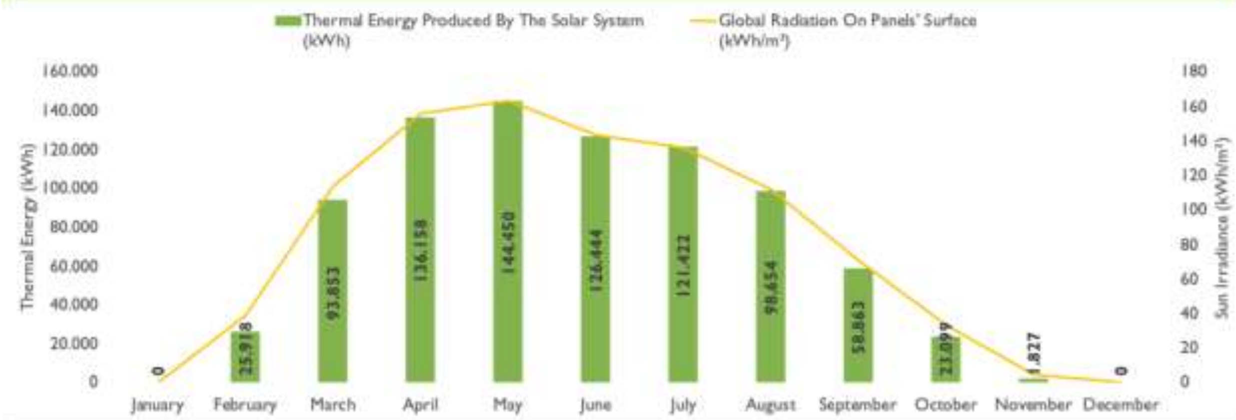
Table 16: Scenario 1 Stella Polaris: Solar field performance (from 23 °C to 53 °C)

Scenario 1 Stella Polaris: Solar field performance (from 23 °C to 53 °C)	
Heat production	564 kWh/ m^2/year
Average yearly efficiency	58%
Energy delivered	818'496 kWh/year
NG[8] savings	100'410 m^3/year
CO_2 savings	170 ton/year

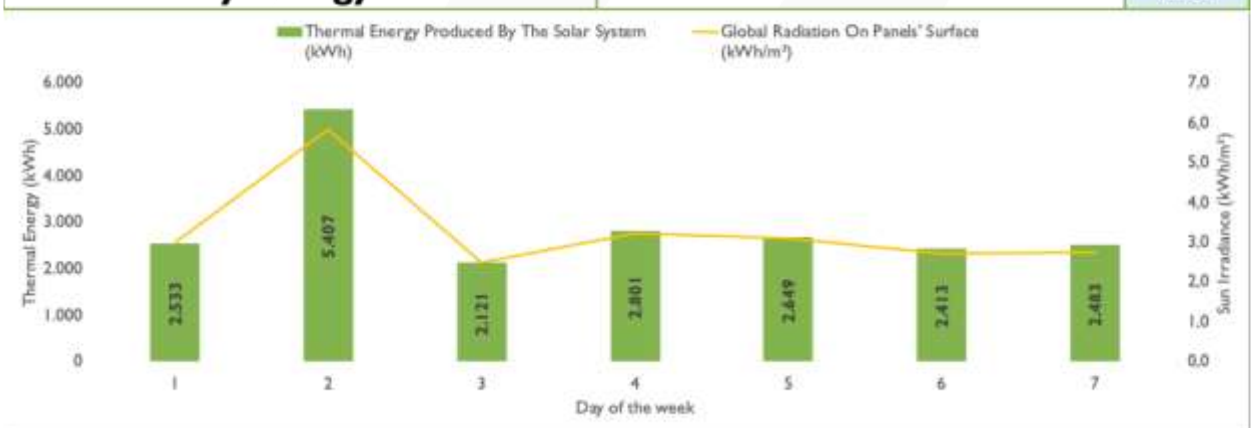
The following charts in Figure 39, illustrates how solar heat production varies throughout the year, on an indicative week, and whithin an indicative day.

[7] A ΔT of 5°C is considered in the heat exchanger (HX) between the solar thermal loop and the application-side (circuit). No thermal storage is considered.
[8] Natural Gas

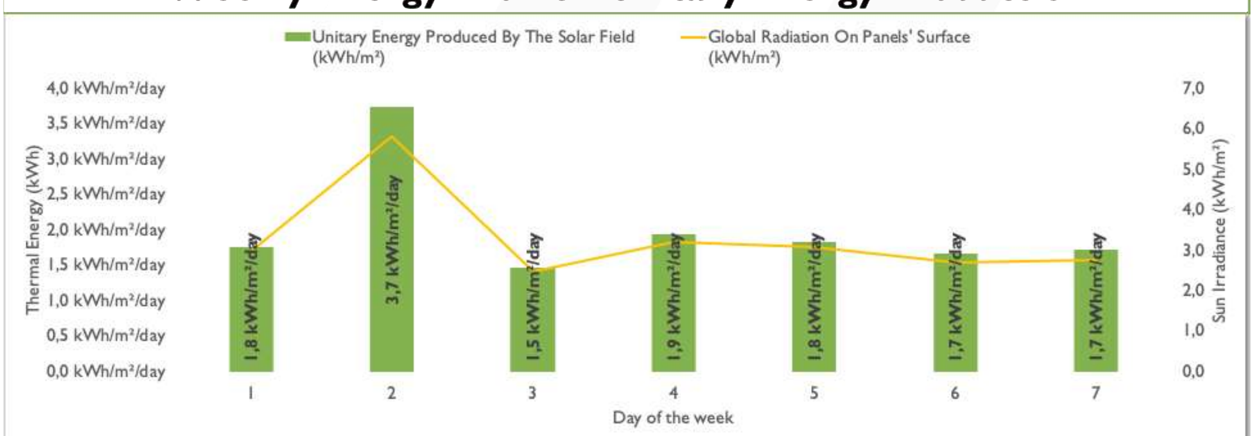
Monthly Energy Profile



Weekly Energy Profile | Week Number | 34



Weekly Energy Profile - Unitary Energy Production



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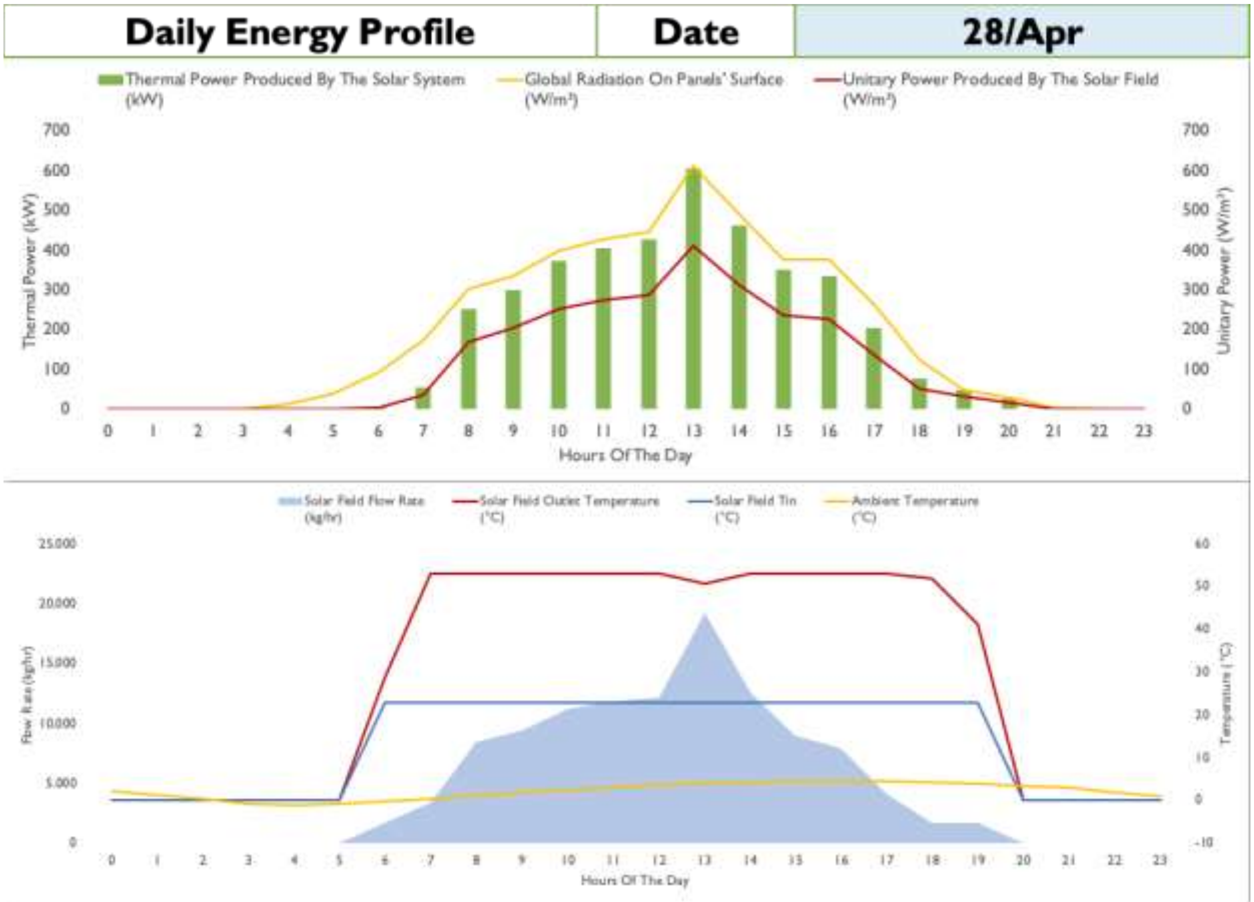
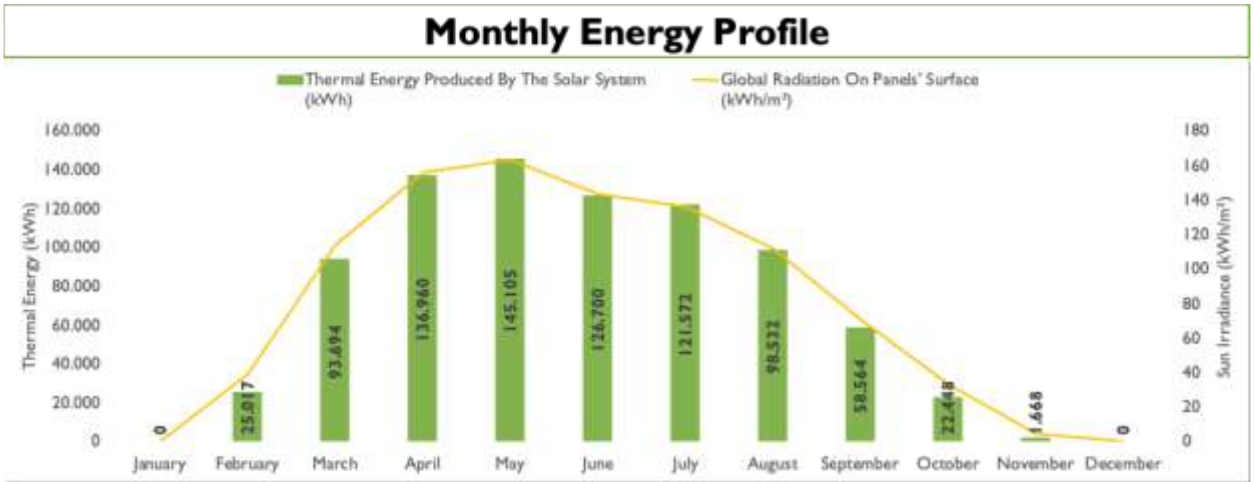


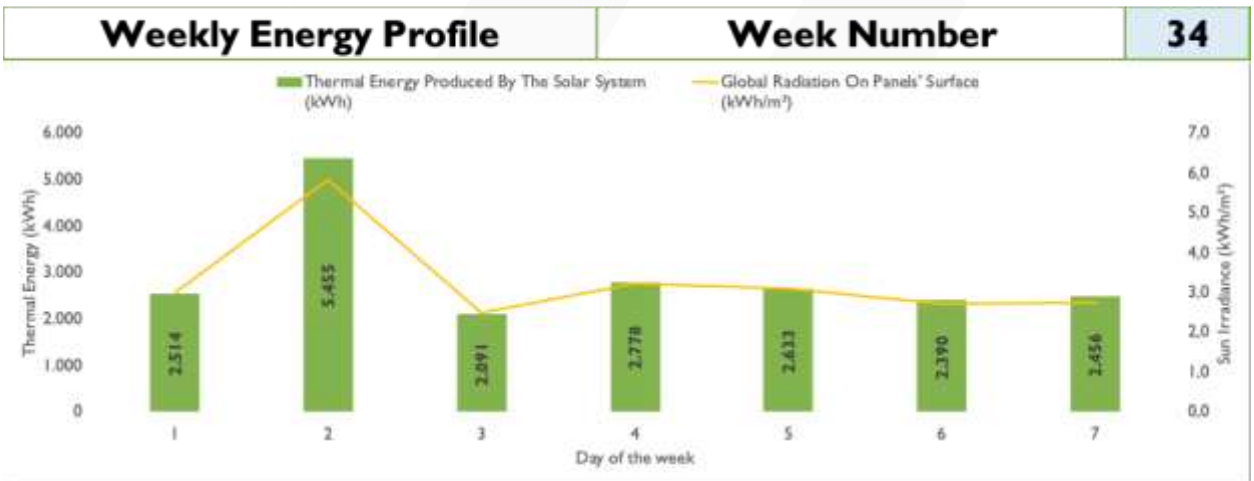
Figure 39: Hourly, Weekly and Monthly Solar heat production profile from the TVP's HVFP technology for scenario-1

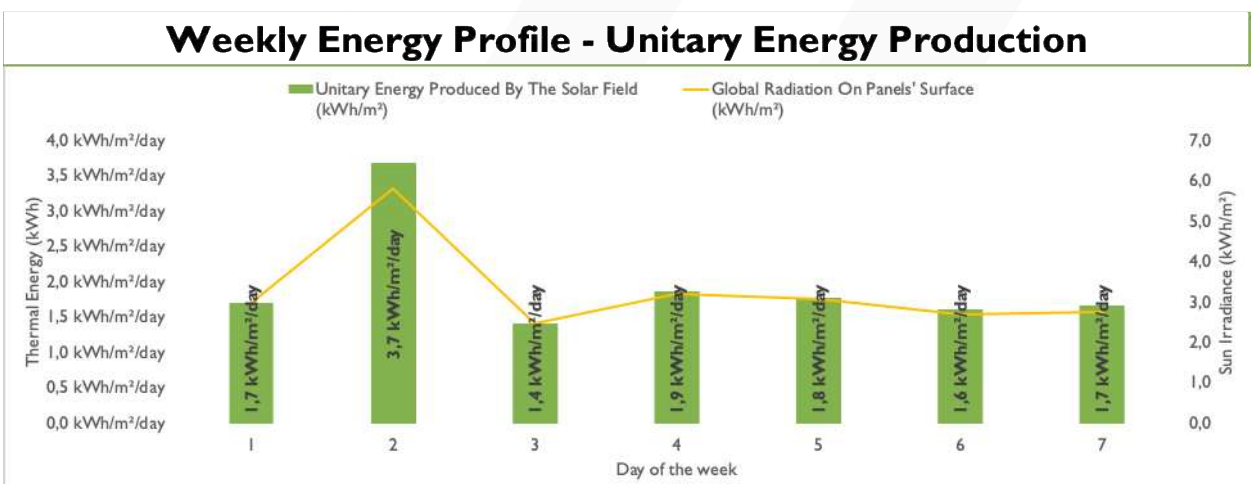
Under the **2nd scenario**, the operating temperature (Tout) of the solar field increases by just 10 °C and therefore, only a slight decrease in the heat delivered is experienced, as shown in Table 17 and Figure 40:

Table 17: Scenario 2 Stella Polaris: Solar field performance (from 23 °C to 63 °C)

Scenario 2 Stella Polaris: Solar field performance (from 23 °C to 63 °C)	
Heat production	549 kWh/m^2/year
Average yearly efficiency	57 %
Energy delivered	816'873 kWh/year
NG savings	100'211 m^3/year
CO_2 savings	170 ton/year


Monthly Energy Profile
Thermal Energy Produced By The Solar System (kWh)
Global Radiation On Panels' Surface (kWh/m²)
Thermal Energy (kWh)
Sun Irradiance (kWh/m²)
0
25.017
93.694
136.960
145.105
126.700
121.572
98.532
58.564
22.448
1.668
0
January
February
March
April
May
June
July
August
September
October
November
December


Weekly Energy Profile
Week Number
34
Thermal Energy Produced By The Solar System (kWh)
Global Radiation On Panels' Surface (kWh/m²)
Thermal Energy (kWh)
Sun Irradiance (kWh/m²)
2.514
5.455
2.091
2.778
2.633
2.390
2.456
Day of the week


Weekly Energy Profile - Unitary Energy Production
Unitary Energy Produced By The Solar Field (kWh/m²)
Global Radiation On Panels' Surface (kWh/m²)
Thermal Energy (kWh)
Sun Irradiance (kWh/m²)
1,7 kWh/m²/day
3,7 kWh/m²/day
1,4 kWh/m²/day
1,9 kWh/m²/day
1,8 kWh/m²/day
1,6 kWh/m²/day
1,7 kWh/m²/day
Day of the week

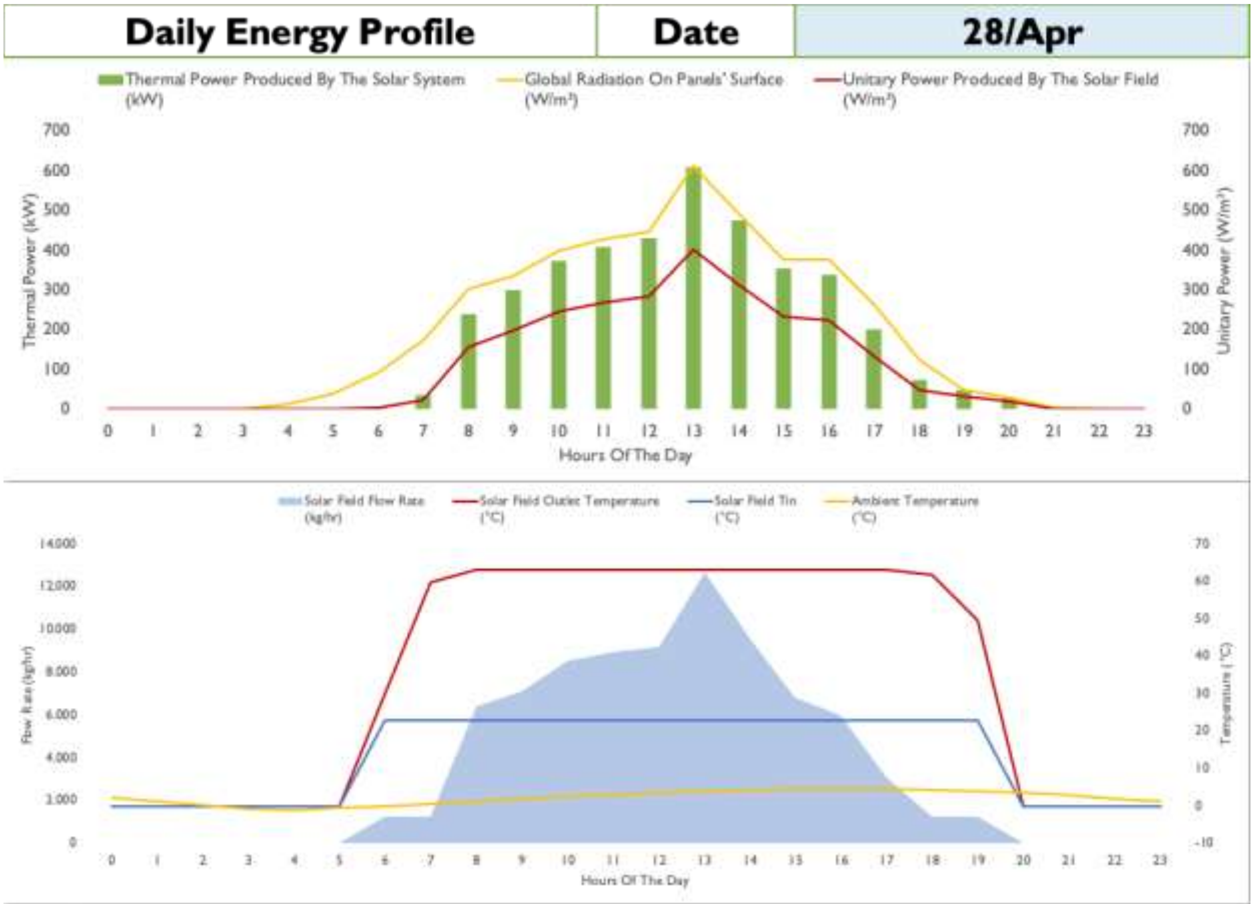
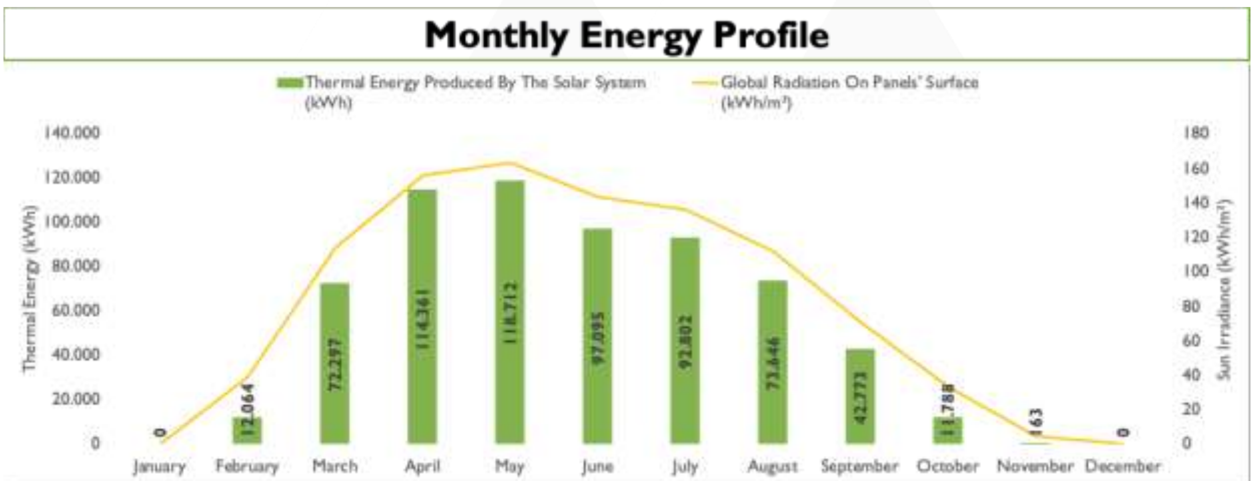


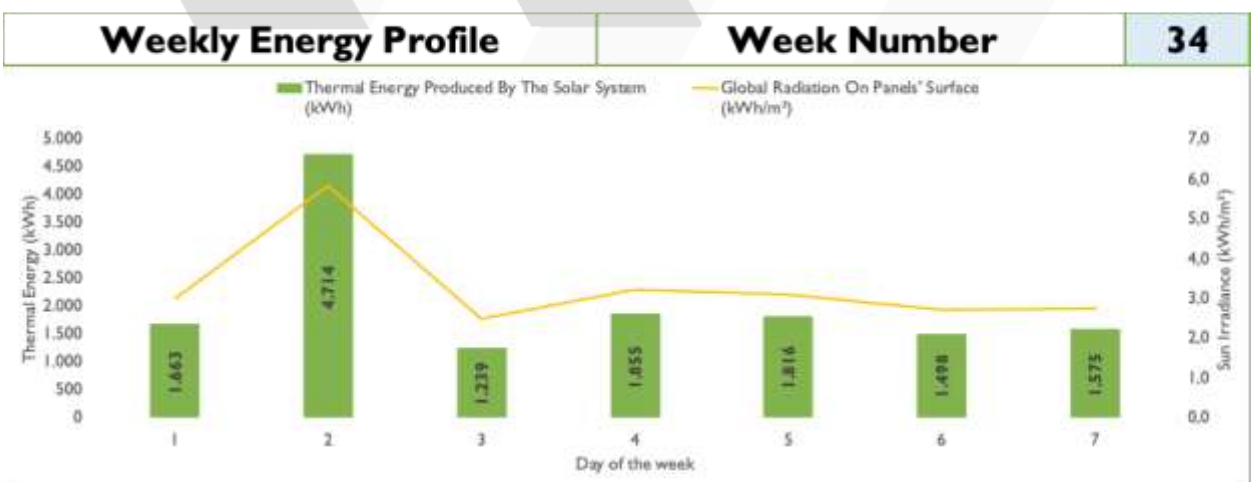
Figure 40: Hourly, Weekly and Monthly Solar heat production profile from the TVP's HVFP technology for scenario-2

Under the **3rd scenario**, both Tin and Tout of the solar field increase significantly, with a much higher increase in the Tin, with the overall objective to upgrade an existing stream of heat. As expected, this change in the operating setpoints has an adverse effect on the efficiency of the solar field, which induces a sharp drop in the overall volume of the heat delivered.

Table 18: Scenario 3 Stella Polaris: Solar field performance (from 83 °C to 93 °C)

Scenario 3 Stella Polaris: Solar field performance (from 83 °C to 93 °C)	
Heat production	388 kWh/m^2/year
Average yearly efficiency	40 %
Energy delivered	609’361 kWh/year
NG savings	74’755 m^3/year
CO_2 savings	126 ton/year





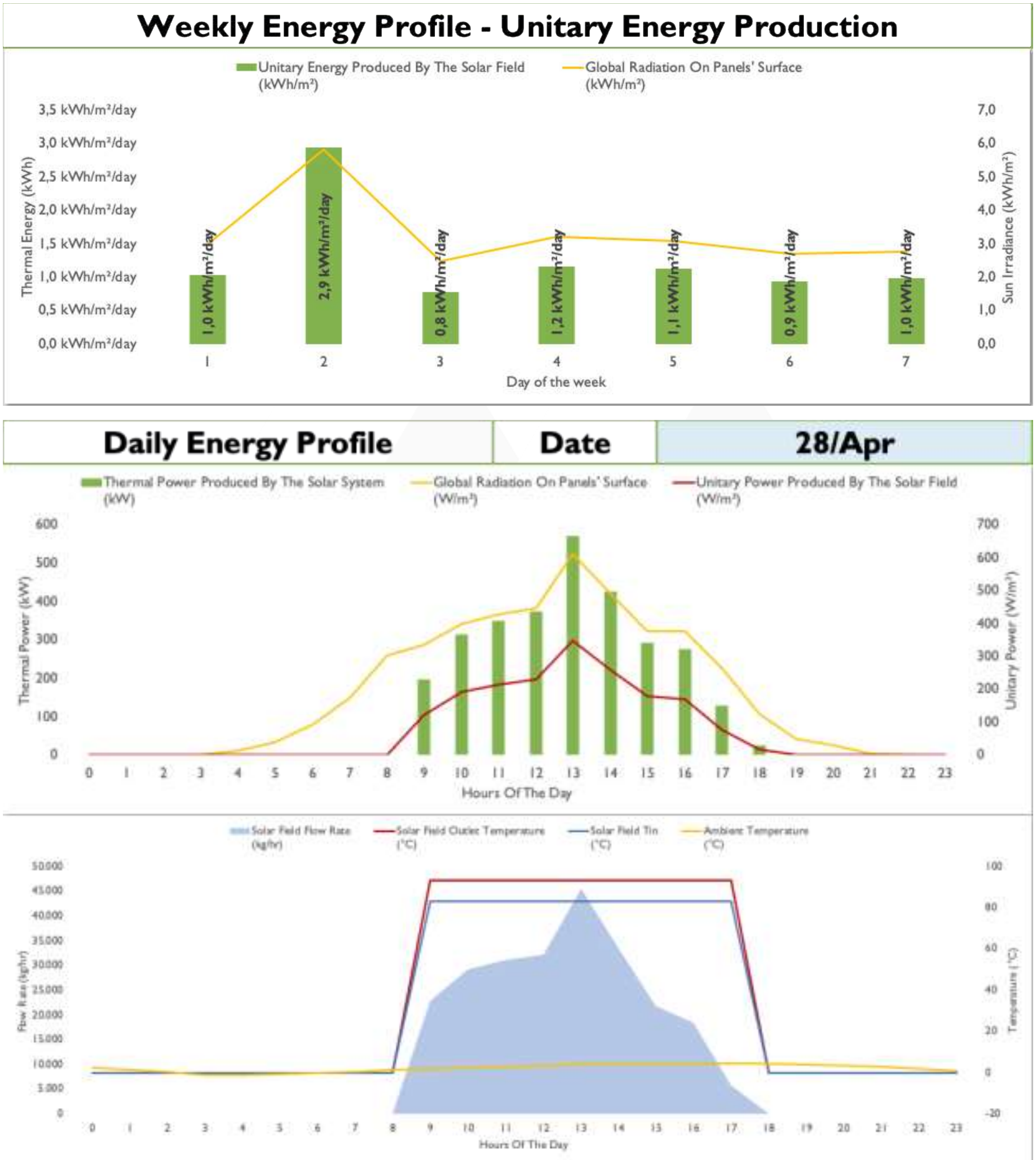


Figure 41 : Hourly, Weekly and Monthly Solar heat production profile from the TVP's HVFP technology for scenario-3

Stella Polaris: solar heat and HP integration potential

What is interesting to examine in the above scenarios is how the cost of solar heat may vary along the different operating temperatures.

For simplicity reasons, we will assume that the cost (CAPEX) of the solar thermal system for the 2nd scenario is around 1 M€ (not far from reality, though it may vary significantly depending on the size and particularities of each installation[9]) and that for the same scenario the operating cost (OPEX) reaches 15 k€[10] on an annual basis. The respective costs for the other two scenarios will be calculated in proportion to their relative size (compared to the 2nd scenario).

Table 19: Levelized cost of solar heat production for the three scenarios

Stella Polaris (North Norway)	SC1 (23 °C to 53 °C)	SC2 (23 °C to 63 °C)	SC3 (83 °C to 93 °C)
Size of the solar field in m²	1472	1512	1638
(a) CAPEX [k€]	974	1000	1084
(b) OPEX [k€/year]	15	15	17
(c) Total cost for a 25-year period [k€] c = a + 25 x b	1349	1375	1509
(d) Annual generation of heat [kWh/year]	818496	816873	609361
(e) Annualised cost of heat (ACoH) [11] [€/MWh] e = c x 1'000 / (25 x d / 1'000)	66	67	99
Normalised ACoH (baseline SC2) [%]	**99**	**100**	**148**

Table 19, shows the levelized cost of solar heat production for the three scenarios. The above calculations show that in locations with particularly low solar irradiance, the cost of solar heat is high even for operation at low temperatures, and may worth only in cases where temperature may be increased from a very low point (e.g. 20-40 °C)

[9] Note: in calculating the cost of solar heat the following cost items are site-specific and have been excluded: cost of preconstruction works, cost of integration, cost of thermal storage, other case-specific costs.
[10] Including maintenance – parts replacement cost
[11] The ACoH does not consider the cost of capital, which is typically included in the calculations of the Levelised Cost of Heat (LCoH).

and just for the wider summer season. Certainly, for locations with higher solar irradiance the cost of solar heat may be lower than 40 €/MWh[12].

Similarly, integration with a HP may worth considering during summer operation, provided that the ST system is used to significantly raise the temperature of the heat source. This may be particular suitable where the use of solar heat may help avoiding a cascade HP system.

[12] Depending on factor such as the level of solar irradiance, the operating temperatures of the ST system, etc..

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13.2.2 Smurfit WestrockWestrock (Czech Republic): Solar heat generation potential & suitability

The SPIRIT's demo-site of Smurfit Westrock is located in the eastern part of the Czech Republic. The annual solar irradiance (GHI) of the location is around 1'100 kwh/m^2/y with almost 70 % of this amount concentrated between April and September.

In this context, two scenarios have been considered: one (**SC1**) for operation between 75 °C (Tin) to 95 °C (Tout)), and another (**SC2**) to serve much higher temperature requirements (125 °C to 135 °C).

The paragraphs below provide an overview of the ability of TVP's High Vacuum Flat Panel (HVFP) technology to deliver heat for each of the these scenarios at top solar-to-heat conversion efficiencies:

Table 20: Scenario 1 Smurfit Westrock: Solar field performance (from 75°C to 95°C)

Scenario 1 Smurfit Westrock: Solar field performance (from 75°C to 95°C)	
Heat production	607 kWh/m^2/year
Average yearly efficiency	47 %
Energy delivered	925'706 kWh/year
NG savings	113'563 m^3/year
CO_2 savings	192 ton/year

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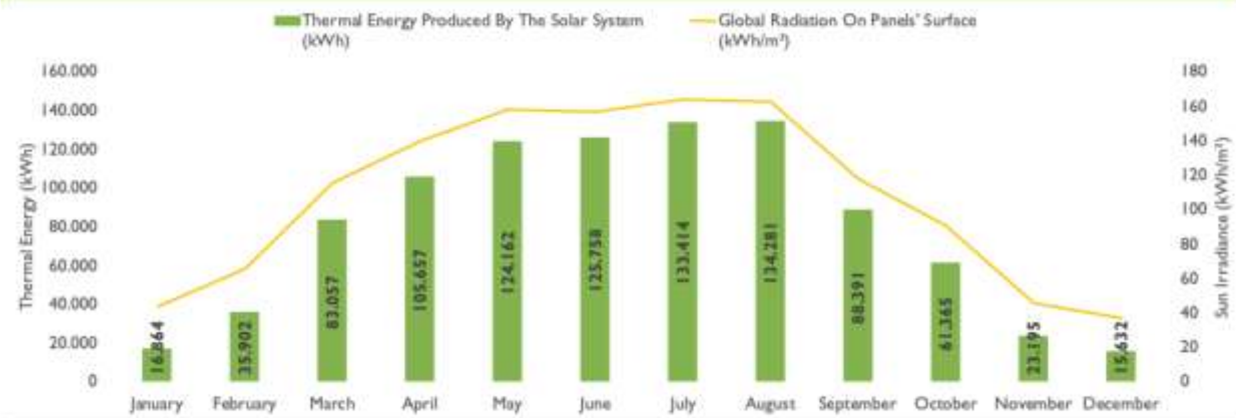
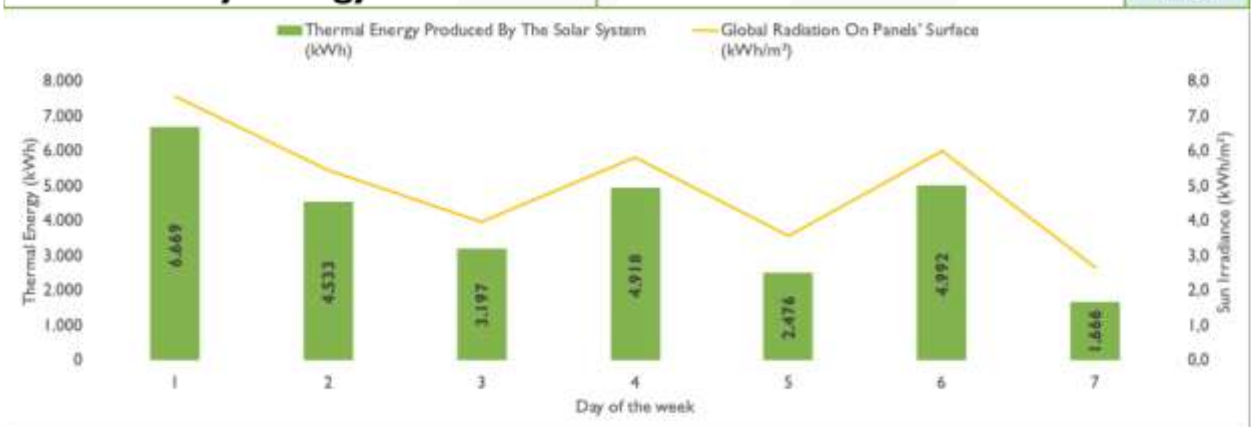
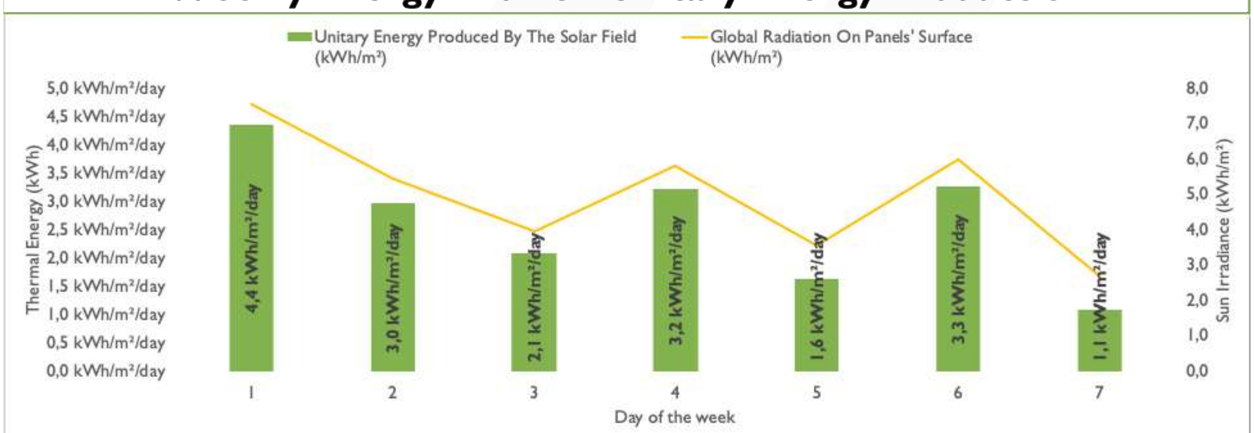
Monthly Energy Profile



Weekly Energy Profile | Week Number | 34



Weekly Energy Profile - Unitary Energy Production



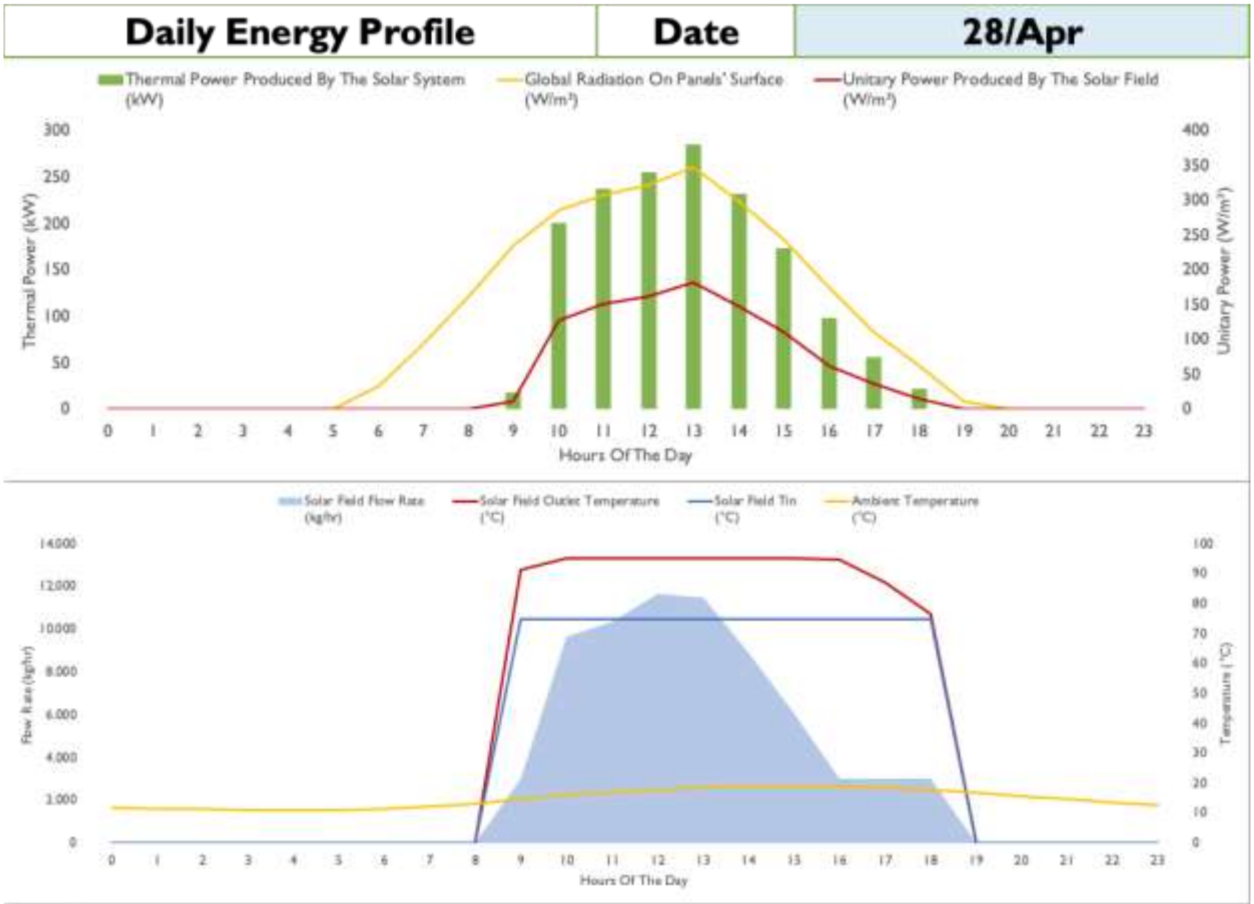


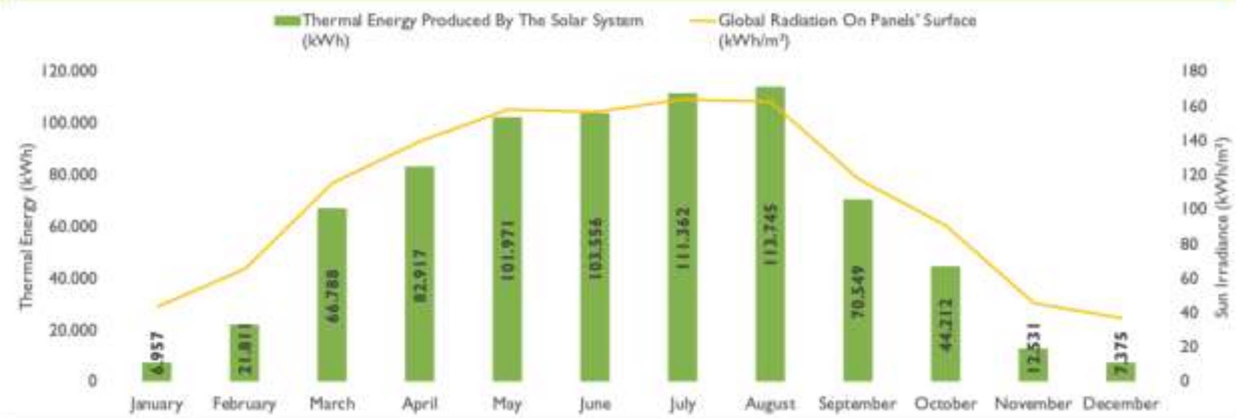
Figure 42: Hourly, Weekly and Monthly Solar heat production profile from the TVP's HVFP technology for scenario-1

This scenario (SC1) may be applied in case where solar heat is directly used as heat source for a HP system or in case where solar heat is used to upgrade waste heat from a lower temperature to a higher one, and thus improve the COP of a HP system.

Table 21: Scenario 2 Smurfit Westrock: Solar field performance (from 125°C to 135°C)

Scenario 2 Smurfit Westrock: Solar field performance (from 125°C to 135°C)	
Heat production	418 kWh/m²/year
Average yearly efficiency	32 %
Energy delivered	714'769 kWh/year
NG savings	87'686 m³/year
CO_2 savings	148 ton/year

Monthly Energy Profile



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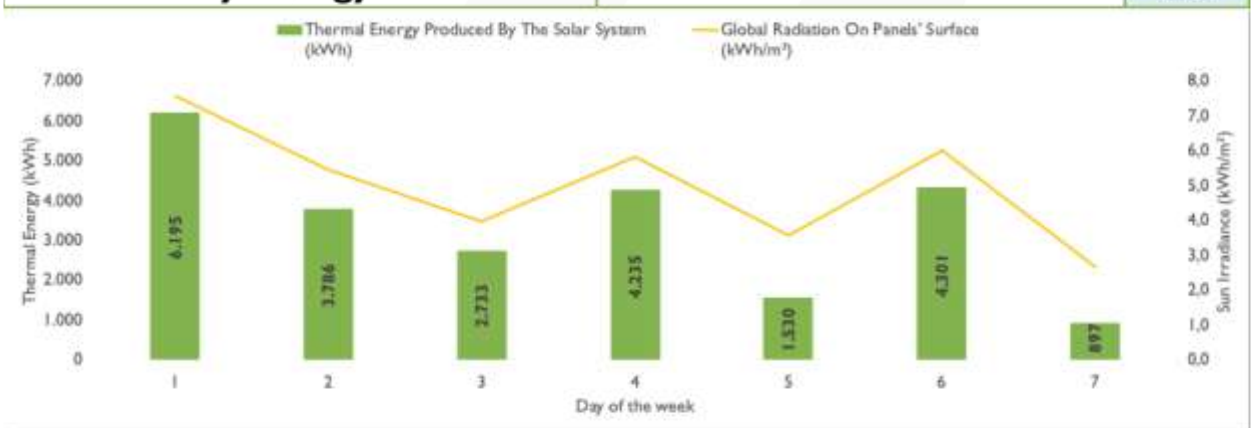
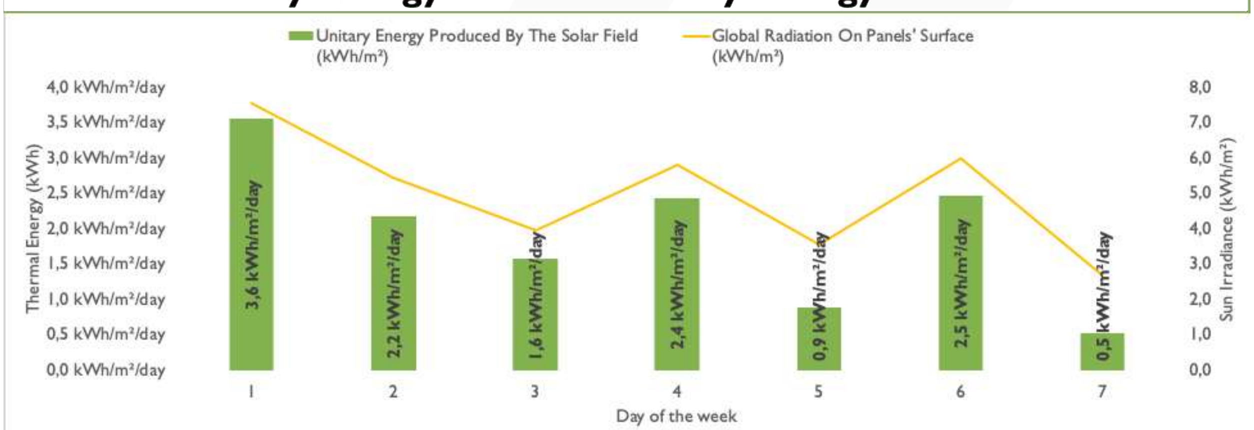


Weekly Energy Profile - Unitary Energy Production



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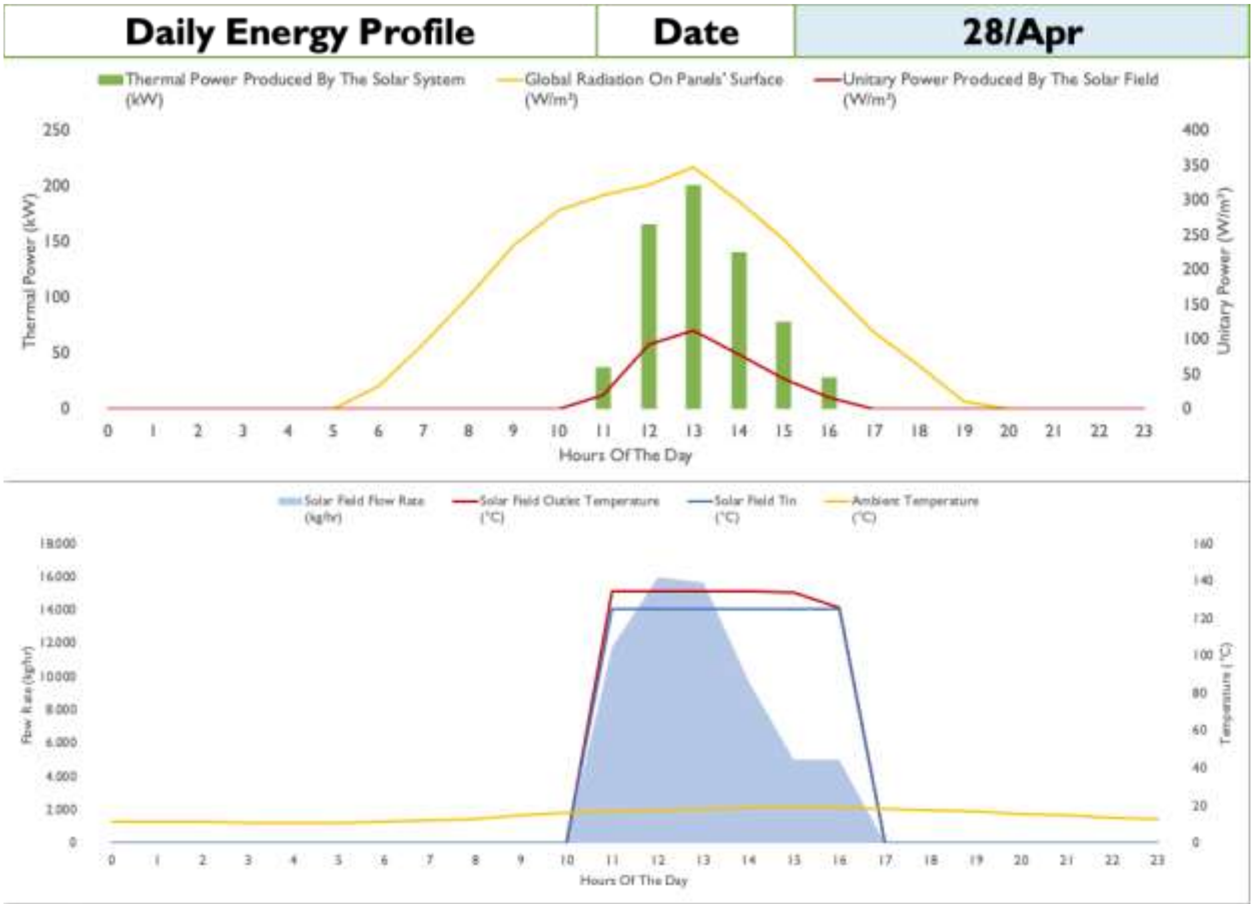

Figure 43: Hourly, Weekly and Monthly Solar heat production profile from the TVP's HVFP technology or scenario-2

<u>*Smurfit Westrock: solar heat and HP integration potential*</u>

The annual solar-to-heat conversion efficiency is severely affected by the increased operating temperature in the 2nd scenario as can be seen from Table 21(it drops from 47 % to just 32 % by raising the average operating temperature ((Tin + Tout)÷ 2) from 85 °C (SC1) to 130 °C (SC2).

By better looking at the simulation results Figure 43, the drop in solar heat generation is much higher during the low irradiance (winter period) reaching up its highest value of -61 % in January. Compared to SC1, the lowest drop (SC2) is experienced from May (-19 %) up to August (-17 %).

Based on the above, the operation of the solar thermal system at different setpoints between summer (May – August) and winter could make sense for two purposes: (i) in case there is heat demand at the range of 120 °C - 130 °C; (ii) in case a higher

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temperature heat source for the HP operation offers a significantly higher heat delivery. The latter case, may be justified if, for instance, the operation of the system under the configuration [ST (at SC2) + HP (at a given electricity consumption)] produces significantly more[13] heat at the sink rather than operation of the system in configuration [ST (at SC1) + HP(at the same level of electricity consumption)].

SC2 may also potentially be used for low pressure steam generation (e.g. 1 barg) during summer. In such a case, a steam compressor will be needed to raise the pressure at the required level, while a dual mode operation of the solar system will apply (i.e. hot water generation during winter and steam generation in summer).

Operation of the ST system under SC1 may also apply in the case where a low temperature stream of waste heat exists (e.g. at 60 °C). In such a case, the ST system may be used to upgrade the waste heat up to e.g. 80 °C - 90 °C before it enters the HP.

[13] What is mentioned here as 'Significantly more' can be quantified as long as the following data are known for different temperatures at the heat source: COP, heat extracted from source, cost of solar heat, and the cost of waste heat (if any). In addition, the cost of electricity should be known.

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13.2.3 Tiense Suiker (Belgium): Solar heat generation potential & suitability

The SPIRIT's demo-site of Tiense Suiker is located in the Flemish part of Belgium. The annual solar irradiance (GHI) of the location is around 1'060 kwh/m²/y (very close to the respective figure for Smurfit Westrock's location) with almost 77 % of this amount concentrated between April and September.

In this context, two scenarios have been considered: one (**SC1**) for operation between 81 °C (Tin) to 91 °C (Tout)), and another (**SC2**) to serve slightly higher temperature requirements (81 °C to 101 °C).

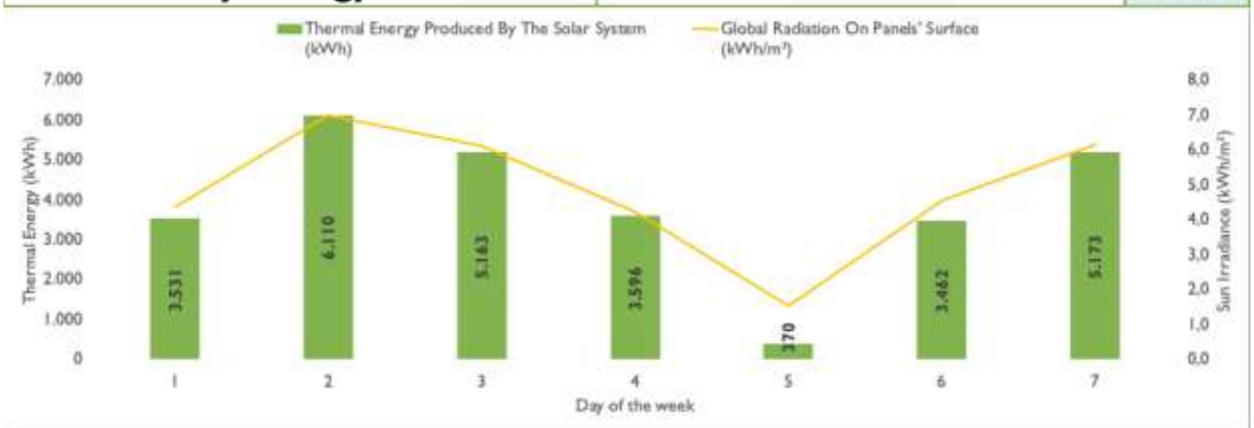
The paragraphs below provide an overview of the ability of TVP's High Vacuum Flat Panel (HVFP) technology to deliver heat for each of the these scenarios at top solar-to-heat conversion efficiencies:

Table 22: Scenario 1 Tiense Suiker: Solar field performance (from 81°C to 91°C)

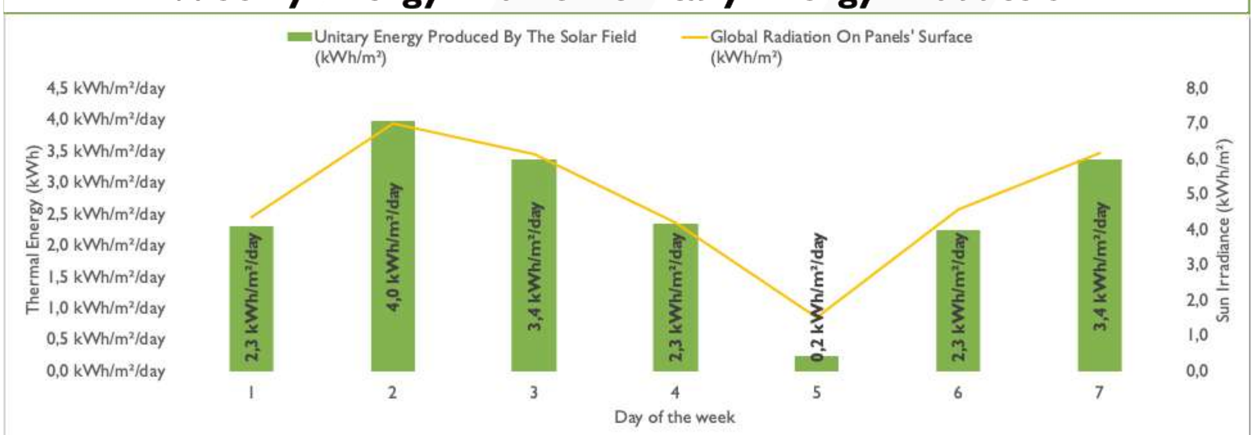
Scenario 1 Tiense Suiker: Solar field performance (from 81°C to 91°C)	
Heat production	564 kWh/m²/year
Average yearly efficiency	46 %
Energy delivered	856'051 kWh/year
NG savings	105'018 m³/year
CO_2 savings	178 ton/year

Monthly Energy Profile

Weekly Energy Profile | Week Number 34



Weekly Energy Profile - Unitary Energy Production



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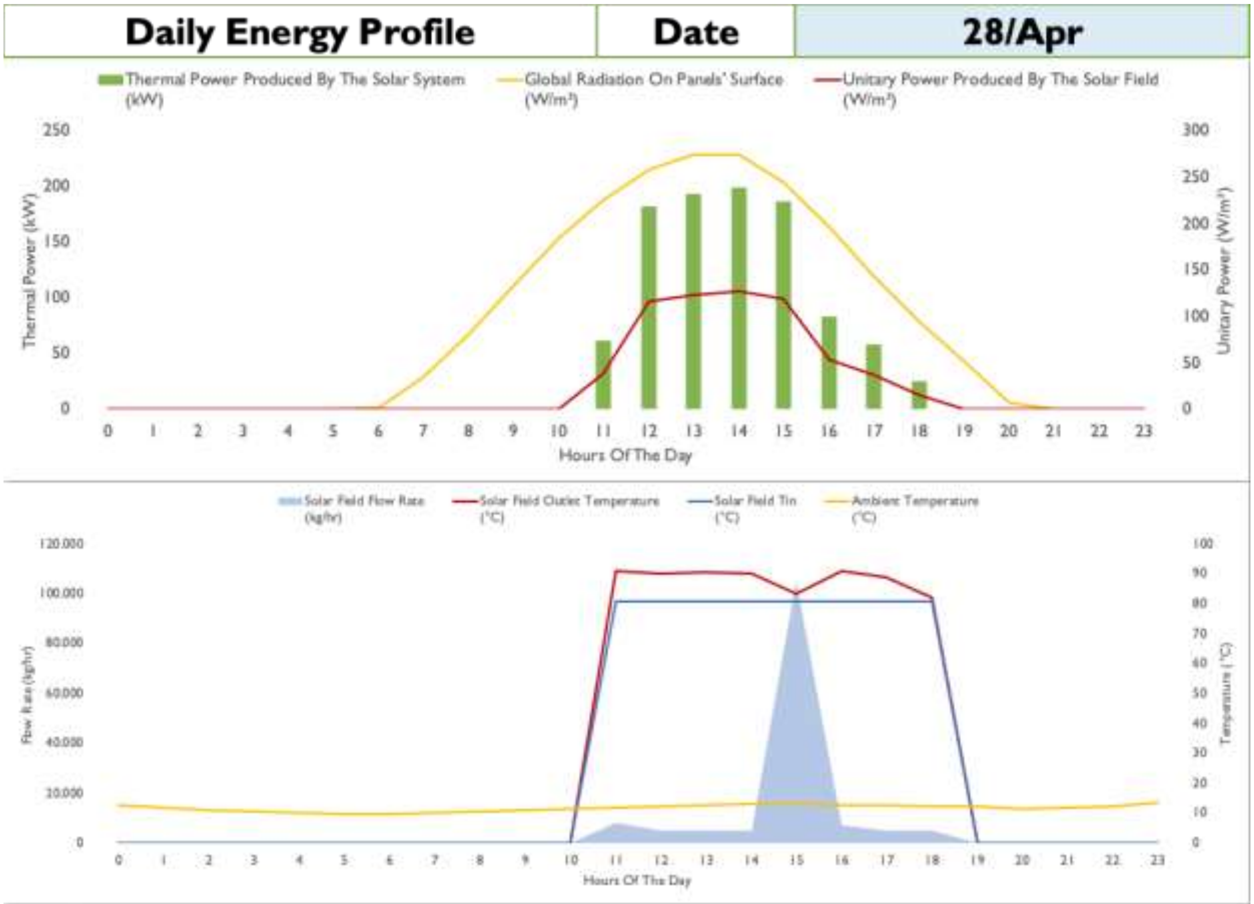
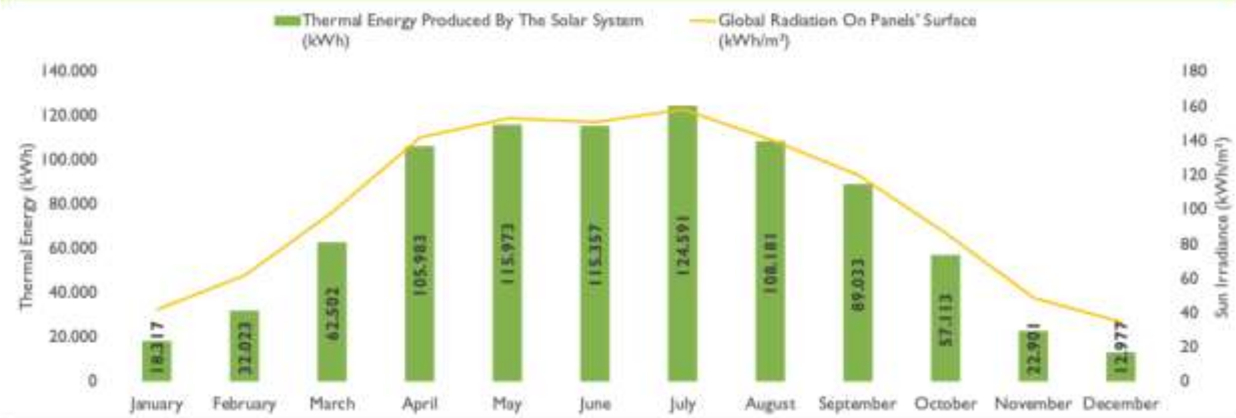


Figure 44: Hourly, Weekly and Monthly Solar heat production profile from the TVP's HVFP technology for scenario-1

Table 23: Scenario 2 Tiense Suiker: Solar field performance (from 81°C to 101°C)

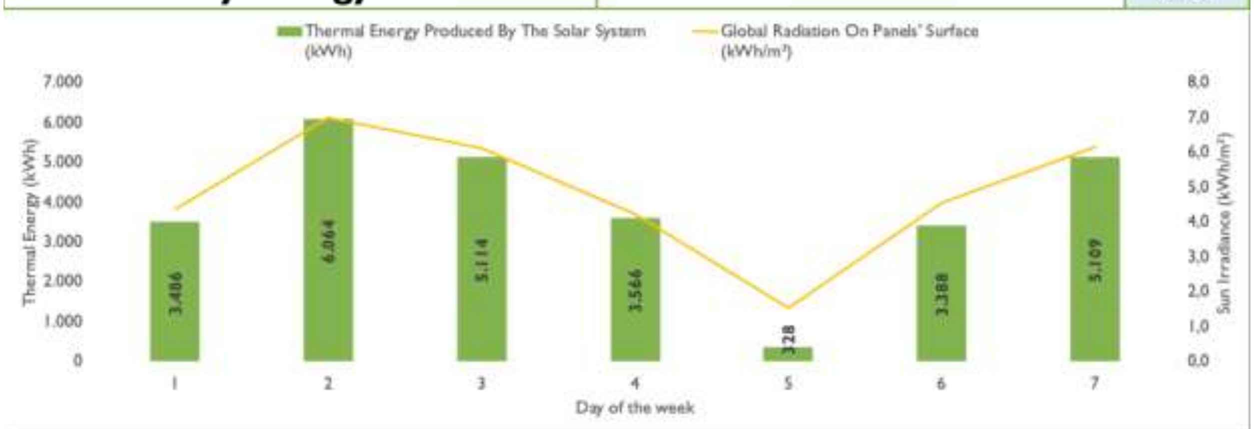
Scenario 2 Tiense Suiker: Solar field performance (from 81°C to 101°C)	
Heat production	545 kWh/m²/year
Average yearly efficiency	44 %
Energy delivered	842'660 kWh/year
NG savings	103'375 m³/year
CO_2 savings	175 ton/year

Monthly Energy Profile

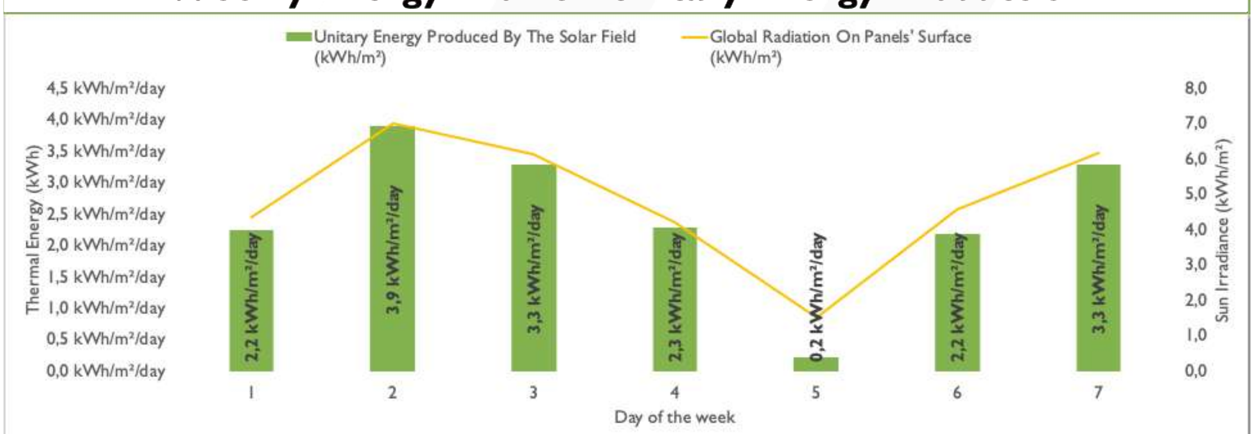


Weekly Energy Profile

Week Number 34



Weekly Energy Profile - Unitary Energy Production



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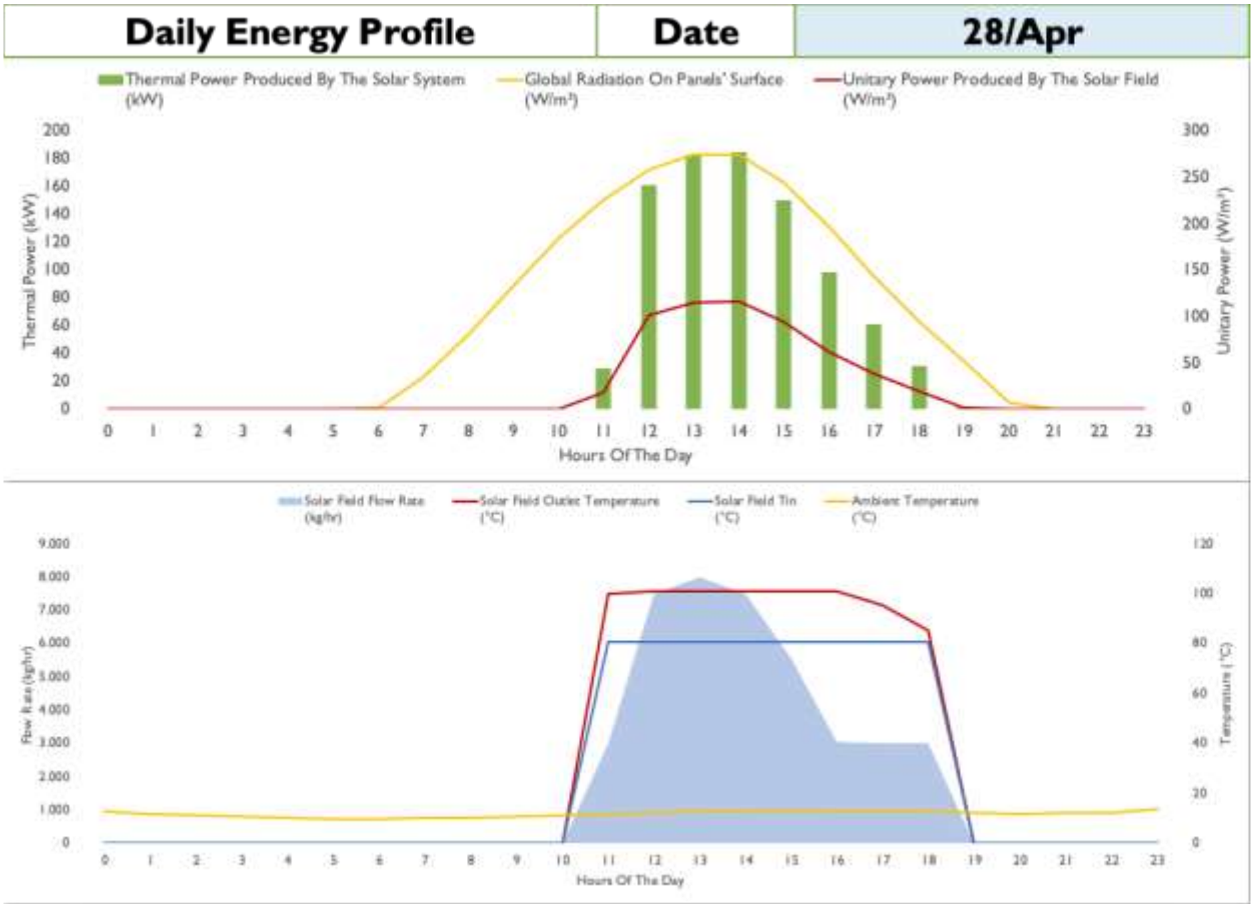

Figure 45: Hourly, Weekly and Monthly Solar heat production profile from the TVP's HVFP technology for scenario-2

Tiense Suiker: solar heat and HP integration potential

Operation at a temperature 10°C higher in SC2 has only a slight impact on the overall efficiency of the solar thermal system (-2pp i.e. from 46 % to 44 %).

However, in this case the major integration challenge comes from the demand side. The sugar production is highly seasonal with the plant operating only for a few months per year (e.g. September to January), which, in addition, are not the best in terms of solar heat generation potential.

One option to match solar heat supply with heat demand is the use of seasonal heat storage, which may add significantly on the cost of heat.

A second option could be the interconnection with a local District Heating Networks (DHN) [14] or another industrial user (under an industrial symbiosis scenario).

13.2.4 Key take aways

Solar thermal

Solar heat generation exhibits certain particularities and comes with some limitations:

- It follows the sun pattern: Irrespective of the location, the solar heat supply has a bell-shaped profile during the day (from sunrise to sunset) and throughout the year (lower as winter approaches and higher as summer closes).
- The higher the peak power the more space (on the ground or rooftop) is required. As an indication, 1 MWth requires around 1’600 m^2 of panels and about 3’000 m^2 of space[15].
- The daily profile may be smoothed by introducing short-term Thermal Energy Storage (TES), while seasonal variations may not, particularly for temperatures close or higher than 100 °C [16].
- Solar thermal technologies may serve a wide range of industrial processes up to 400 °C. The current report examines the High Vacuum Flat Panel (HVFP) technology that has been developed and marketed by TVP Solar SA (partner in the SPIRIT project). HVFP-based systems can produce heat currently up to 180°C.
- In European climates and locations, it is worth considering the operation of the solar systems at different operating temperature setpoints between winter (lower operating T) and summer (higher operating T) periods.
- Dual mode operation could be also an option: generating hot water (e.g. 80 °C -90 °C during winter) and low-pressure steam (e.g. 1 barg - 3 barg) during the summer period.

[14] *‘As part of their commitment to the Local Energy and Climate Pact (LEKP), Flemish municipalities have to make a heating plan. Therefore, heating and cooling plans are not mandatory but 98% of Flemish municipality are committed to do one’*. Source: https://energy-cities.eu/countries/belgium/

[15] This figures apply for TVP’s High Vacuum Flat Panel (HVFP) technology. Other solar thermal technologies may require substantially more space.

[16] Seasonal thermal energy storage is typically applied for low temperatures and large district heating installations, while Thermochemical storage or other long-term storage solutions are still under development and too expensive to be considered.

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Solar thermal and High Temperature HPs

The optimal solution of ST and HTHP integration depends on parameters such as the heat demand profile, the availability or not of waste heat, the location of the industrial consumer, the HP technology, etc. In general, the following options may be considered depending on the location – solar irradiance:

Table 24: Integration potential of ST+HTHP+TES+WH based on solar irradiance

		Solar Irradiance (GHI)					
		(700-1000) kWh/m²/y		(1000-1500) kWh/m²/y		>1500 kWh/m²/y	
		Winter	Summer	Winter	Summer	Winter	Summer
Solar Thermal	Source	?	✓	✓	✓	✓	✓
	Sink	×	×	×	?	?	✓
	<70°C	✓	✓	✓	✓	✓	✓
	70-100°C	?	✓	✓	✓	✓	✓
	>100°C	×	×	?	✓	✓	✓
	Steam	×	×	×	✓	✓	✓
Waste heat	Source	✓	✓	✓	✓	✓	✓
HP	Sink	✓	✓	✓	✓	✓	✓
TES	Source	✓	✓	✓	✓	✓	✓
	Sink <100 °C	×	✓	×	✓	✓	✓
	Sink >100 °C	×	×	×	✓	✓	✓

Table 24 indicates potential uses of a heat upgrade systems based on solar thermal and HP integration. As an example, a location with solar irradiance (GHI) of 1'100 kWh/m²/year, may use an integrated solution combining ST (as heat source < 100 °C), WH (heat source), HP (heat sink) and TES (heat source <100 °C) during both winter and summer time. At the same location, generation of solar heat >100 °C may not be feasible during the winter period. Similarly, the use of solar heat directly for the process requirements may be possible in places with GHI > 1500 kWh/m²/year. Still at these locations, integration with a HTHP and TES could help extending the operating hours of the system beyond daytime or during low irradiance hours.

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13.3 Integration concept for paper production

In this subsection, a Solar Thermal (ST) and Heat Pump (HP) integration concept will be discussed for a paper production plant. Two such scenarios have already been presented in the previous subsection (the Smurfit Westrock case). Here, a more detailed analysis will be made.

For simplicity reasons, it is assumed that whatever the size of the solar thermal system is, it can be accommodated in the premises of the industrial consumer. In that sense, we can consider scenarios where the share of solar heat ranges for low (e.g. up to 10 % - 15 %) to relatively high (e.g. 40 %).

In general, the solar thermal system can serve three purposes:

i. To provide the heat source and/or complement existing waste heat sources (during the winter season, or throughout the year) to a HTHP;
ii. To provide low-pressure steam during the summer period, when it can operate efficiently at significantly higher temperatures (a steam compressor may be used to increase the pressure of the solar steam), and
iii. To provide solar heat for pre-heating the return condensate of the steam boilers or provide heat directly like to the process during the summer period.

In this report, two scenarios of around 500 kW peak each, are examined:

- Scenario 1 Paper Industry: The ST system is used to increase the temperature of the waste heat and thus allow the HTHP to operate at a lower ΔT (and thus higher COP). Solar heat will be used to increase the temperature of waste heat from 60 °C to 80 °C in a location close to Smurfit Westrock in the Czech Republic.
- Scenario 2 Paper Industry The ST system is used as above during the 'winter' period (October-March), whereas during the summer period (April-September) the ST system will operate at higher temperatures (Tin: 118 ºC; Tout: 135 °C) for low pressure steam generation.

As a result, both scenarios will decrease the required electricity for the HP operation by either decreasing the operating hours or increasing the COP.

The simulation results for the two scenarios are presented below. For each of them a detailed simulation has been performed by using TRNSYS software.

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Table 25: Scenario 1 Paper Industry: Solar field performance (from 65 °C to 85 °C)

Scenario 1 Paper Industry: Solar field performance (from 65 °C to 85 °C[17])	
Location	Hradec nad Moravicí, Czechia
GHI [kWh/m²/year]	1'111
Solar Field Peak Power [kW]	512
Gross Area [m²]	744
Installed Area [m²]	1'312
Application[18] Tin [°C]	60
Application Tout [°C]	80
Heat production [kWh/m2/year]	661
Average yearly efficiency [%]	51 %
Energy delivered [kWh/year]	471'743

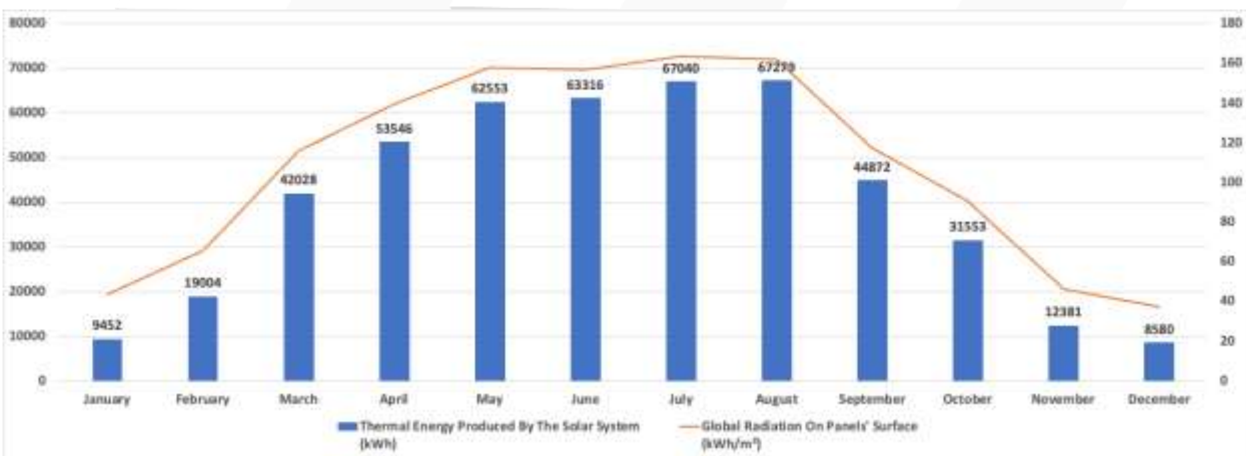

Figure 46: Yearly solar heat production Scenario-1

[17] Tin and Tout of the solar (primary) circuit
[18] It refers to the secondary circuit (demand side)

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Table 26: Scenario 2 Paper Industry: Dual mode: Winter → hot water (from 65 °C to 85 °C); Summer → Solar steam generation at 2 barg (from 118°C to 135°C)

Scenario 2 Paper Industry: Dual mode: Winter → hot water (from 65 °C to 85 °C); Summer→ Solar steam generation at 2 barg (from 118°C to 135°C)	
Location	Hradec nad Moravicí, Czechia
GHI [kWh/m2/year]	1'111 for Apr-Sep
Solar Field Peak Power [kW]	536
Installed Area [m2]	1'524
Gross Area [m2]	864
Application Tin [° C]	60 (Oct-Mar); 118 (Apr-Sep)
Application Tout [° C]	80 (Oct-Mar); 135 (Apr-Sep)
Heat production [kWh/m2/year]	442 345 [kWh/m² for Apri-Sep]
Average efficiency [%]	42.3 Oct-Mar 38.5 Apr-Sep
Energy delivered [kWh]	138'977 for Oct-Mar 279'850 for Apr-Sep 418'8270 /year

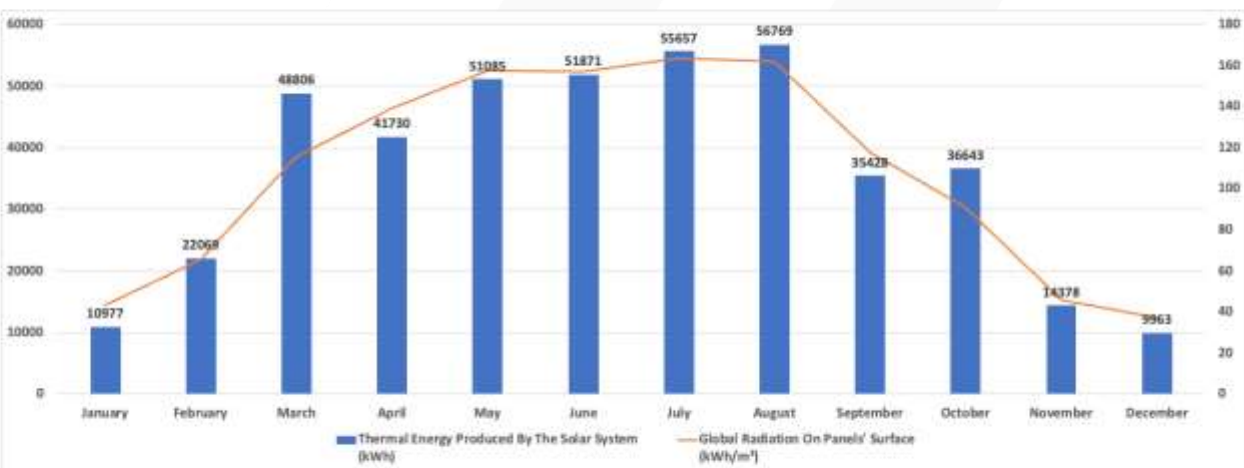

Figure 47: Yearly solar heat production Scenario-2

The total energy produced by the solar field is 435’376 kWh/year (at dual mode) compared to the 374101 kWh/year if steam mode was applied throughout the year. Therefore, the dual mode operation brings a gain of 16% in solar heat production.

13.3.1 Comparative analysis

- Both scenarios are dimensioned on the basis of approximately 500 kW peak power. To achieve this figure during the summer period, the dual mode system is significantly larger (+16 %) than Scenario 1. Reaching higher temperatures requires a larger number of solar thermal panels.
- Another advantage of operating at lower temperature is reflected on the solar-to-heat conversion efficiency with Scenario 1 exhibiting an average yearly efficiency of 51%, with the equivalent figure as low as 34% for steam generation throughout the year. The drop in efficiency appears clearly in the thermal energy production diagram of Scenario 2 when comparing solar heat production in March (hot water at 85 ºC) and in April (steam at 2 bar). Apparently, the solar irradiance is higher in April, whereas heat production is lower.
- Scenario 1 can be used only as a heat source for a HTHP, while Scenario 2, during the summer period, can be partially provide low pressure steam directly to the process.
- Paper industries tend to operate 24/7 with a relatively constant load. Given this load profile, the solar system can be dimensioned to match the heating load during the summer period (we assume that no seasonal storage can be applied).
- For extended operation of the ST system (e.g. beyond daylight hours) and/or for flexibility reasons, a Thermal Energy Storage (TES) solution may be considered. In such a case, the solar field can proportionally be increased to match the heat demand throughout a 24-hour cycle in a summer day. However, as solar steam cannot be stored, in this case the ST system in Scenario 2 may be configured differently to provide e.g. hot water at ‘high’ temperature (and not steam). Then, the stored hot water could be used as a heat source for a HTHP for operation at extended hours.
- For both scenarios, a TES solution can be dimensioned based on the underline goal (e.g. flexibility during daytime, extended hours operation, etc.).
- For Scenario 2, a steam compressor may be required to increase the pressure of solar steam and match the requirements of the paper production process.

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13.3.2 Integration concept for paper production

The heat pump integration concept within a paper manufacturing mill depends strongly on the heat source utilized. If the solar thermal collector field and tank are sized sufficiently, the system can achieve a significantly higher COP than a system using a lower temperature excess heat source, which in paper production is often humid air. Figure 48 shows the overall suggested system layout to integrate a heat pump and ST with the process.

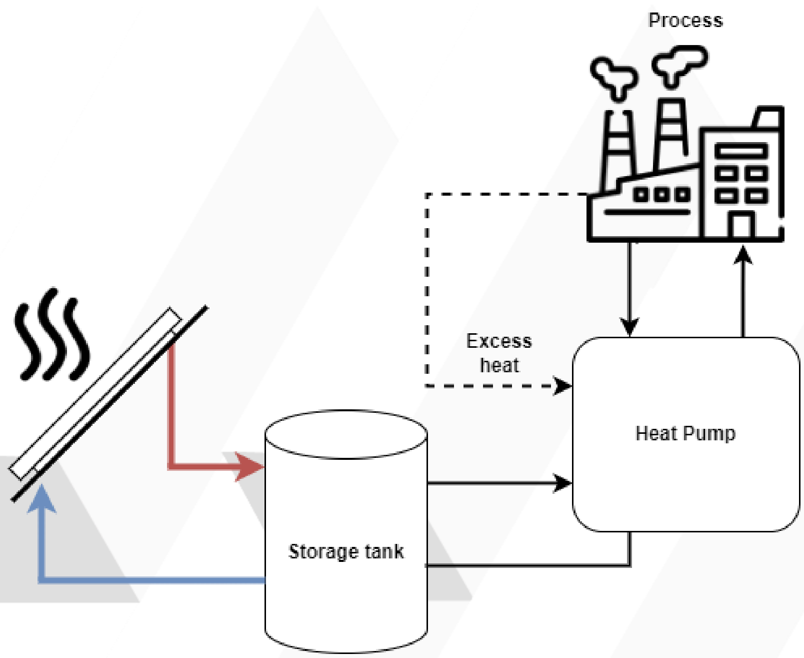

Figure 48: Heat pump integration with solar thermal and heat storage

Figure 49 shows the daily load profile of ST. Inter-day fluctuations are visible due to varying conditions such as cloud cover. To compensate for the time-dependent nature of solar thermal heat generation, it is highly beneficial to combine ST with a storage. The solar thermal storage system should be dimensioned to have sufficient heat available to serve as heat source of the heat pump.

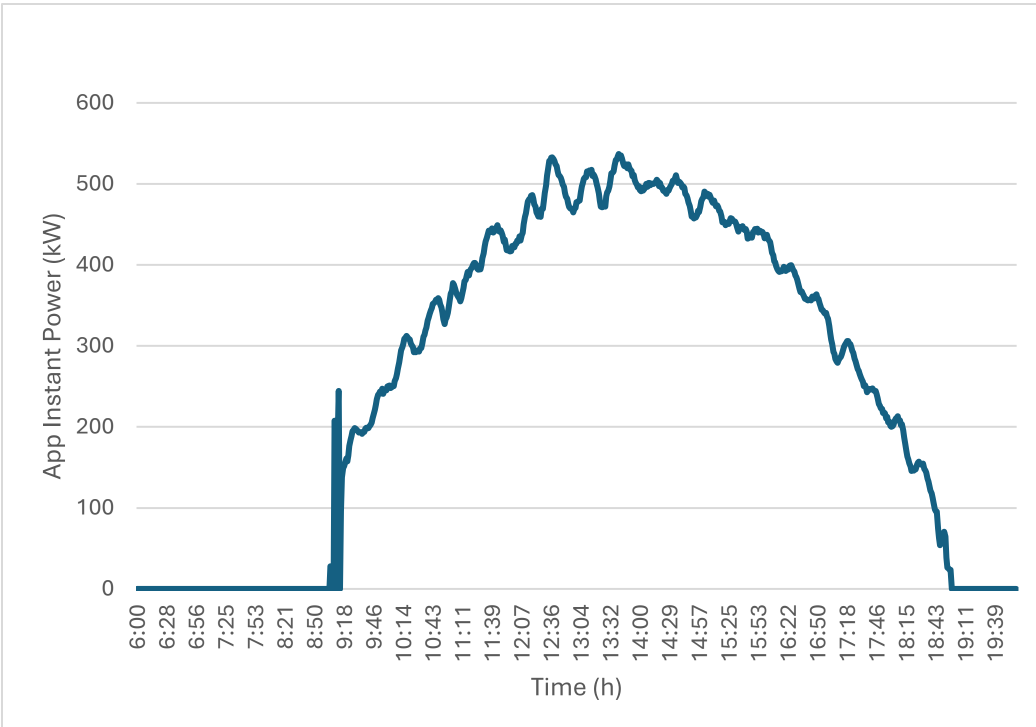

Figure 49: Daily profile of solar thermal production

A basic comparison between the following cases is carried out below and shown in Table 27. The cases are (a) a heat pump with excess process heat (40 °C) as heat source and (b) a heat pump with solar thermal (80 °C) as heat source. Both are compared to a conventional natural gas burner in terms of CO_2 emission reduction considering the carbon intensity of the Danish electricity grid and 6000 annual operating hours. The system is required to deliver 2 MW saturated steam at 175 °C.

Table 27: Performance of a 2 MW heat pump producing steam with (a) excess process heat (40 °C) as heat source and (b) solar thermal (80 °C) as heat source

Case	(a)	(b)
COP (-)	2.36	3.6
CO_2 reduction (%)	86	91
Q_{source} (kW)	1153	1445
P_{HP} (kW)	847	555

Case (a), which utilizes the humid air process heat stream, requires a significantly larger heat pump of 847 kWe to supply the 2 MW steam, compared to case (b), a combined solar thermal and heat pump system, which needs a heat pump with an installed electric power of only 555 kW. This reduction substantially lowers electricity costs. However, operating the solar thermal–heat pump system for 16 hours per day demands a large solar collector field and thermal storage. Assuming a solar irradiation for a Nordic country (3.5 kWh/m²/day) and a collector efficiency of 0.6; the required collector area would be approximately 11,000 m². This is comparable to 1.5 football fields. Based on a simple energy balance, the corresponding water storage tank volume would be around 249 m³. To obtain more precise sizing and evaluate economic trade-offs, a detailed assessment of the annual and daily load profiles is necessary.

Generally, as outlined in the comparison of Saini et al. [13], in regions with less favorable meteorological conditions, the levelized cost of heat pumps is lower than that of a solar thermal system. However, in regions with higher direct normal irradiance, such as southern Europe, solar thermal can outperform heat pump integration and should be considered as a cost-effective alternative for steam generation. Common barriers to integration include limited collector area, the need for process modifications or downtime during retrofit, and interfacing with legacy automation systems. The optimal combination of a heat pump and a solar thermal system depends on the local climate, electricity prices, and capital expenditures, all of which must be considered to properly size the solar collectors, storage, and heat pump for the lowest overall cost of steam generation.

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14. CONCLUSIONS

This deliverable has presented comprehensive integration concepts and practical guidelines to decarbonize industrial heat through high-temperature heat pumps and solar thermal technologies. Covering both brownfield and greenfield applications in nine key energy-intensive processes, the report provides detailed, sector-specific pathways for achieving substantial energy and carbon reductions.

Across the various integration concepts and demonstration cases analyzed:

- Milk Powder Spray Drying: Energy savings in the range of 40 % to 70% are achievable when high-temperature heat pumps are integrated in place of natural gas boilers.
- Shrimp Cooking: Heat pump systems can deliver 45 %to 85% energy savings compared to conventional heating.
- Sugar Production: Energy use can be reduced by 70 % to 86% through heat pump integration with process waste heat recovery.
- Paper Production: Integration strategies yield 52 % to 62% energy savings, primarily by recovering and upgrading low-grade waste heat.
- Baking Ovens: Electrification and heat recovery strategies achieve energy savings from 30 % up to 75 %, depending on process temperatures and oven types.
- Distillation: The application of mechanical vapor recompression and/or high-temperature heat pumps reduces energy demand by 70 % to 95 % relative to traditional systems.
- Brick Drying: Partial and full heat pump integration results in 55 % to 70% primary energy savings.
- Brewing: Combined heat recovery and heat pump electrification concepts reduce electricity use per hectolitre of beer brewed by 25 % to 52 %, operating with a COP of up to 3.4.
- Slaughtering: Electrifying hot water and steam supply with heat pumps achieves energy savings in the 70 % to 85 % range.

In all cases, the addition of solar thermal technologies and thermal energy storage can further enhance system performance, and lower operating costs, particularly during periods and locations of high solar availability.

Collectively, the integration of high-temperature heat pumps and solar thermal solutions offer a transformative pathway for industrial sites—delivering consistent energy savings typically ranging from 40 % to 90 % across studied applications. When

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implemented alongside grid decarbonization, these strategies also enable deep reductions in CO_2 emissions, positioning the European process industries to meet both near- and long-term climate targets.

Thorough planning—incorporating energy mapping, process integration studies, advanced controls, and phased deployment—is essential for maximizing benefits and managing challenges unique to each site. By applying these guidelines and insights, industry leaders and engineers are well-positioned to accelerate the transition to efficient, flexible, and future-ready industrial heat supply.

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