Performance Monitoring of an 800m² Solar Thermal Plant with Evacuated Flat Plate Collectors Coupled to a DHN

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Abstract

The performances of a 800 m² solar thermal plant coupled to a large District Heating in Geneva has been monitored for more than one year. The solar field is composed of 400 high performance evacuated flat plate collectors manufactured by TVP Solar. It has an average operating temperature above 80°C. This plant has been equipped with sensors to monitor and follow its performances over time. In 2021, the solar plant has injected 536 MWh in the DHN which corresponds to a specific yearly productivity of 684 kWh/m²/y or 45 % of average efficiency. Performances were compared between 2021 and the first half of 2022, with no observed performance degradation. The monitoring will be pursued at least until the end of 2024.

Keywords: solar thermal district heating system, performances monitoring, high vacuum flat plat collector

1. Introduction

The Geneva canton utility company (Service Industriels de Genève or SIG) owns and operates an important portfolio of District Heating Network (DHN). The "CADSIG" DHN is one of the largest and oldest DHN operated by SIG. This DHN built in the 1960's uses a mix of heat produced by natural gas combustion and by a Municipal Waste Incineration Plant (MWI). It has delivered more than 240GWh of heat in 2013/14 to satisfy Space Heating (SH) and Domestic Heat Water (DHW) demand in more than 3 Million m² of housing (Quiquerez and Faessler, 2015). It operates at relatively high temperatures with a forward temperature fluctuating between 115 (winter) and 90°C (summer) and a return temperature around 72°C +/- 2°C all year round. It has average yearly losses of ~10%. The CADSIG DHN energy mix in 2017 is given in the Table 1 below.

Tab. 1: Energy mix of the CADSIG DHN in 2017

Heat producer	Total heat injected
Heat from natural gas boilers (η = 96 %)	204 GWh
Heat from the MWI	125 GWh
Expected solar heat production	0.5 GWh

The use of solar heat in DHN has gained an important interest in the last decade following the successful pioneering large scale applications in Denmark (Perez-Mora et al., 2018). Countries like Germany and Austria (Tschopp et al., 2020) have recently developed subsidy schemes to support the growth of large solar thermal plant. DHN is a very promising application for solar heat for different reasons. Large solar fields can benefit from important economy of scale which drives down the cost of solar heat making it more competitive. In addition, the average efficiency and specific productivity are typically larger than for smaller solar plants mainly because the regulation is more efficient on larger plants (Noussan et al., 2017). The rebound observed in the market of solar thermal collectors in 2018/2019 can partly be explained by the growth of the number of solar thermal plants for DHN and process heat applications.

As the operating temperatures of DHN can be relatively high, it is necessary to find innovative solar thermal technologies able to produce heat at medium to high temperatures with reasonable efficiency and moderate over-costs. This is one of the objectives of the recent IEA-SHC task 68 ("IEA-SHC task 68 - Efficient Solar District Heating Systems," n.d.). Evacuated Flat Plate collectors (EFP) use high vacuum as highly efficient thermal insulation to increase the efficiency and operating temperature range up to 150°C (Benz and Beikircher, 1999). EFP is a very promising technology for operation above 70-80°C. For example, Moss et al (Moss et al., 2018) have recently shown by simulation that, when operated at 85°C, the yearly specific productivity could be double

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with EFP than with classical flat plate collectors. The main challenge of this technology is to prove that it can maintain a sufficient level of vacuum inside the collector over its lifetime (20 years or more).

Swiss based company TVP Solar has developed a very efficient EFP mainly for industrial process heat and DHN applications. This collector is one of the first EFP commercially available. The efficiency of their product is particularly superior to alternative technologies above 50K of temperature difference between ambient and solar collector (Beikircher et al., 2015). The TVP Solar collectors are insulated by vacuum (~< 0.1Pa) thus strongly reducing thermal losses due to gas convection and conduction. The vacuum is maintained throughout the life of the collector thanks to a getter pump, which has been designed to absorb gases outgassing from the solar collector components and compensate micro leaks (Benvenuti, 2013).

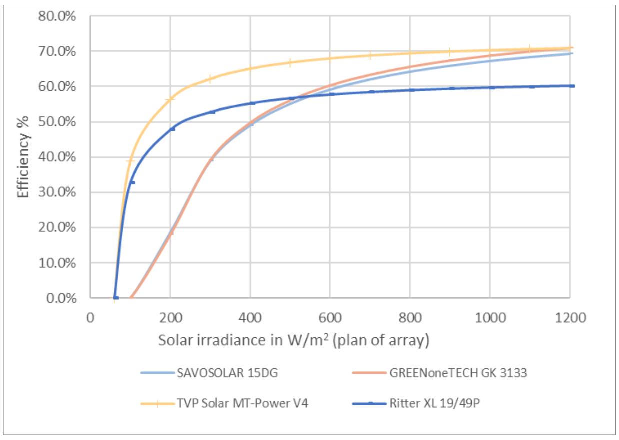


Fig. 1 Efficiency comparison for different solar collectors commercially available established with the Solar Keymark certificates (for an average collector temperature of 70°C and an ambient temperature of 25°C)

Compared to other solar collectors on the market for an average temperature of 70°C (Figure 1), the MT-Power collector from TVP Solar offers the best performance. It should be noted that this collector maintains very good conversion efficiencies at low irradiances (< 500 W/m^2) where competing technologies have lower efficiencies. This characteristic is very interesting for applications in northern Europe where the share of solar energy with irradiances lower than 500W/m^2 is very important. In Geneva, for example, more than 50% of the solar energy corresponds to irradiance lower than 500 W/m^2. Each of the TVP Solar collectors is also equipped with a Spot Check^{TM}, which can be used to check the vacuum quality: when the vacuum integrity of one collector is compromised, the Spot Check^{TM} color will change from pale yellow to transparent white. The high thermal insulation compared to classical solar thermal collector explains the higher performances of TVP collector. The thermal losses are very low allowing to maintain good efficiency with low irradiance of when operating with important temperature difference with ambient.

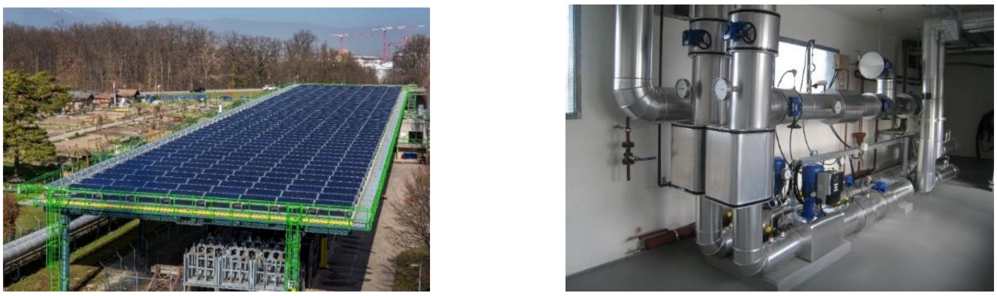
2. Solar thermal plant characteristics

In 2019, SIG decided to test the performance and reliability of the TVP products in a decentralized large pilot plant called “SOLARCADII” connected to “CADSIG” DHN (see characteristics in Table 2). This large pilot plant is composed of two different parts: (1) the solar thermal plant connected to (2) the heat transfer station by a plate heat exchanger (HEX). The solar thermal plant has total gross area of ~800m^2 and is composed of 400 TVP MT-Power collectors. The solar field has been integrated on a ~1’700m^2 existing metallic structure close to the DHN and is oriented with an azimuth angle of 4° W (see Figure 2). The collectors are arranged in 50 lines separated by 0.8m, composed each of 8 collectors installed with a tilt angle of 17.5°. This solar plant is the first one to use EFP technologies at this scale.

Tab. 2: Main characteristics of the SOLARCAD II solar plant

Solar central name	SOLARCAD II
Owner	Services Industriels de Genève (SIG)
Solar plant engineering company	TVP Solar SA
Solar thermal field	
Solar thermal collector model	EFP MT-POWER v4.3
Total number of collectors	400
Solar thermal field total surface	784 m²
Nominal operating temperature	75-95°C
Peak thermal power at 85°C (T_a=25°C ; G=1000 W/m²)	537 kW
DHN and DHN connection	
CAD auquel est raccordé la centrale	CAD SIG
Type of DHN connection	Decentralized, Return/Return
Inlet temperature at the solar substation	72°C +/- 1.5°C ;

The heat transfer fluid is a 11.1% glycol/water mixture. Two pumps are used to circulate the fluid with a flowrate varying between 5 and 23m^3/hr. In case of emergency, the solar heat is dissipated in a 610kW cooling tower to prevent overheating of the solar field. The HEX has a rated power of 500kW and is used to hydraulically decouple the DHN from the solar plant. The heat transfer station circulates demineralized water from the DHN return pipe at a maximum flowrate of 47m^3/h trough the HEX to be heated by solar heat before being re-injected into the DHN return pipe. Due to the very low yearly solar fraction, it was not necessary to integrate a heat storage (<0.5%).



(a) (b)

Fig. 2 Picture of the solar field on the metallic structure (a) and of the heat transfer station (b) (integrated in a room below the metallic structure)

The regulation of the solar plant is done as follow (see Figure 3):

1. **Plant startup:** the fluid is circulated in the solar field once the solar irradiation exceeds 200W/m^2 for more than 5minutes (Loop 1 in Figure 3). The three-way valve is positioned so that the fluid circulates only in the solar field until the outlet solar field temperature reaches 80°C. Then the three-way valve is operated to circulate the fluid in the HEX (Loop 2 in Figure 3). After a 120sec delay, the pump on the DHN side is activated and solar heat is injected in the thermal grid (Loop 3 in Figure 3).

2. **Plant in operation:** in operation, the solar field flowrate is regulated to maintain the outlet solar field temperature at 80°C until reaching the maximum flowrate. The DHN pump is regulated at minimum flowrate when the temperature gain on the DHN side is lower than 3°C. It follows the solar flowrate with a proportional factor above this threshold until the maximum flowrate is reached.

3. **Plant shutdown:** when the irradiance is below 200W/m^2 for 5 minutes, the plant shutdown process is initiated. The flowrate on the solar side is reduced to a minimum and stopped. The pump on the DHN side is stopped when the temperature gain in the HEX is less than 1°C. The plant is then ready to start up again.

In addition, there are routines to protect the plant from freezing (on DHN and solar side) and to dissipate solar heat in the cooling tower in case it is not possible to inject the heat in the DHN.

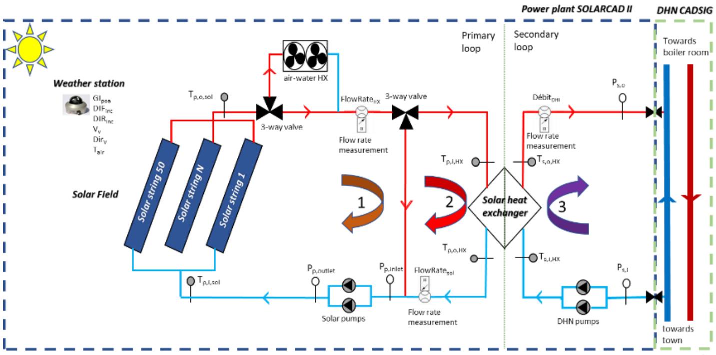


Fig. 3 Hydraulic layout of the "SOLARCADII" plant with the position of each sensor used for performances monitoring

The shading mask has been generated from the middle of the solar field to evaluate the potential irradiation losses due to various shading sources. The Figure 4 presents the shading mask with far shading, close shading (mainly building and chimney) and self-shading. The total losses due to shading represents to less than 1% of the total yearly irradiation.

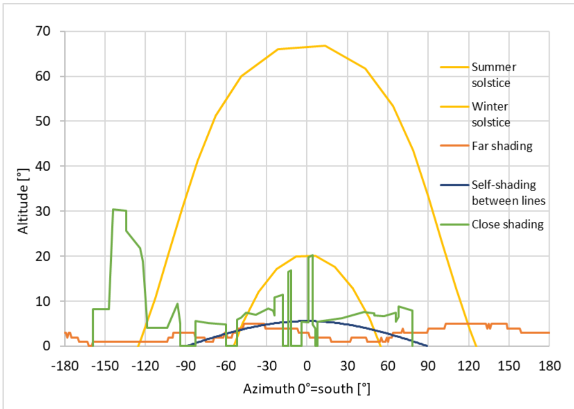


Fig. 4 Shading mask taken in the middle of the solar field

3. Solar thermal plant monitoring

The solar thermal plant performances are monitored since its start up in January 2021. Sensors were installed in order to measure the meteorological conditions and to perform energy balances between the different plant sections. The installed sensors positions are given in the Figure 3.

There are temperature sensors at the inlet and outlet of the solar field and solar exchanger (Endress Hauser TMR31). On the solar side, the flowrate is measured at two points (in the solar loop at the outlet of the solar field and after the HEX) using two Yokogawa DY050 flowmeter. Additionally, a temperature sensor has been installed at the outlet of each line on the solar field. A weather station has been installer close to the middle of the field to measure ambient temperature, humidity, wind speed and direction. The solar irradiance is measured with a pyranometer installed in the plan of array (SPN1 from Delta-T) also located close to the middle of the solar field. This pyranometer measures both the global and diffuse irradiances. The direct irradiance can be deduced by calculation. On the DHN side, the solar heat injected is measured with a heat meter (Calec Energy master coupled with a Krohne flowmeter). The signal of each sensor is acquired at a one-minute sampling rate by the PLC which controls the plant. Measurement data are then sent daily on a server where they are archived in a database for further utilization.

In order to analyze the solar plant performance, various Key Performance Indicators (KPIs) have been used. A definition of each of those KPIs is given below. The total heat produced yearly by the solar field (E_{sol}) corresponds to the total amount of heat produced by the solar field (using inlet and outlet solar field temperature sensors). The total heat produced yearly by the solar plant (E_{DHN}) is calculated by summing the heat injected in the DHN. The solar field efficiency (η_{Sol}) is calculated as follow:

$$\eta_{Sol} = \frac{E_{sol}}{E_{Sol\_poa}} \qquad \text{(eq. 1)}$$

where E_{Sol_poa} is the total amount of global solar irradiation received in the plan of array during one year. Similarly, the efficiency of the solar plant (η_{tot}) is calculated using as follows:

$$\eta_{tot} = \frac{E_{DHN}}{E_{Sol\_poa}} \qquad \text{(eq. 2)}$$

The yearly specific heat productivity of the solar field $E_{Spec,sol}$ is calculated as the ratio of the heat produced by the solar field (E_{sol}) divided by the solar field gross are (784m^2). Similarly, the specific productivity of the solar plant $E_{Spec,tot}$ is defined as the ratio of the total solar heat injected in the DHN (E_{DHN}) divided by the solar field total gross area (784m^2).

4. Solar plant performances analysis

The solar thermal plant yearly performances have been calculated using the measures realized in 2021. In total, 535MWh were injected into the DHN in 2021 for a global irradiation of 1528kWh/m^2/yr in the plane of array (poa). This corresponds to a yearly specific productivity of 684kWh/m^2/yr and an average conversion efficiency of 45 % for an average solar field operating temperature above 80°C. At the solar field level, a yearly efficiency of 46.4% has been measured which corresponds to a specific productivity of 705kWh/m^2/yr. This high productivity and efficiency demonstrate the interest of the EFP technology for heat production above 80°C, particularly when compared to the typical conversion efficiency of conventional flat plate collectors (between 35 and 40% at 80°C, Furbo et al., 2018). This 10 to 30% difference is explained by the higher conversion efficiency of the EFP from TVP Solar at low irradiance (<500W/m^2).
The yearly electrical coefficient of performance (COP) has also been estimated using the pumps efficiency curve given by the suppliers and the measured flowrates. The COP is defined as the ratio of the heat production to the electricity consumption required to move the heat transfer fluid in the plant and to regulate the plant. For 2021, a COP of 38.5 has been calculated for the plant, while for the solar field only a COP of 53.5 has been found due to significant pressure losses on the solar side. For the solar plant, typical COP reported in the literature are in principle above 100.
A Sankey diagram has been generated to visualize the energy losses for the first year of operation of the plant (see Figure 5). This figure shows that the diffuse radiation represented ~33% of the total yearly irradiation. 10% of the yearly irradiation has been lost because of the 200W/m^2 irradiation threshold. This threshold could certainly be reduced in order to increase the field productivity. The solar HEX losses are negligible.

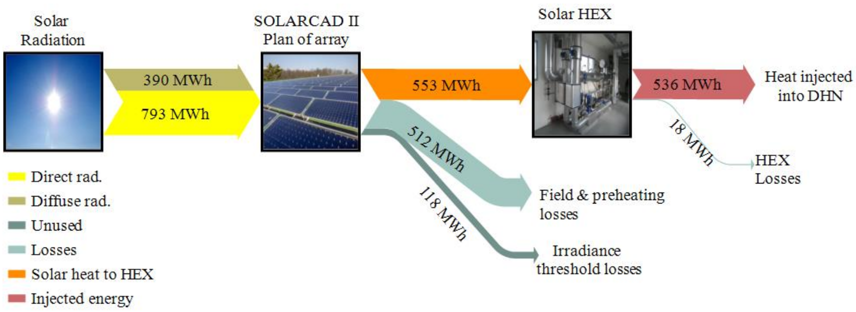


Fig. 5 Sankey diagram representing the main losses of the SOLARCADII installation for year 2021

The Figure 6 shows the temperature and flowrate profile in different section of the installation during a clear sky day (16th of June 2021). The preheating phase is started as soon as the irradiance is above 200W/m^2 for five minutes (05:45). Once the solar field has reached 80°C, the heat starts to be injected first in the solar HEX and then in the DHN (07:00). The flowrate in the solar loop is adjusted in order to regulate the solar operating temperature until the irradiance is too high to maintain the temperature at 80°C (above 450W/m^2). Above this irradiance, the temperature in the solar loop increases up to 95°C when the solar irradiance is maximum (~1'000W/m^2). Then the temperature of the solar field decreases and the injection in the solar HEX is stopped when it is below 80°C (17:00). The solar pump is still operating at reduced flowrate until the irradiance is below 200W/m^2 and the solar field temperature below 75°C.

The relatively high temperature reached in the solar loop when the irradiance is above 450W/m^2 reduced the solar field efficiency. Nevertheless, with the TVP technologies, the efficiency reduction when operating 95°C instead of 80°C is very small (<5%). Thus, it seems not necessary to increase the flowrate in the solar loop to better regulate the operating temperature.

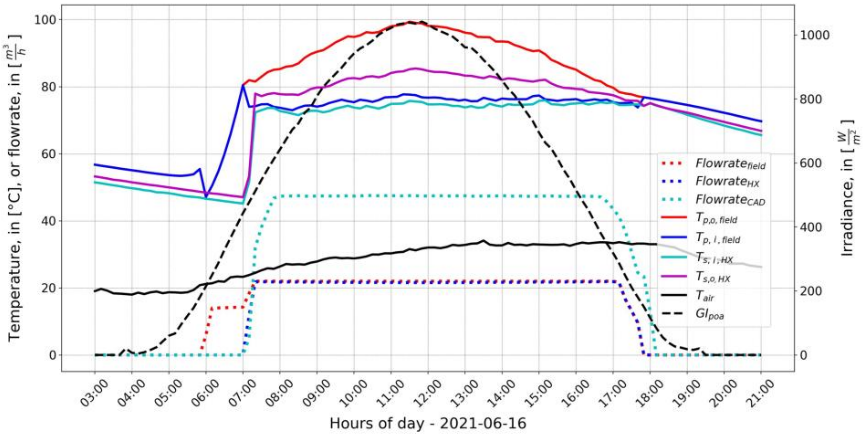


Fig. 6 Clear sky day typical solar plant production profile

5. Solar plant performances stability

As mentioned above, EFP is a very promising technology to increase the specific productivity and to produce heat at temperature above 80°C. The advantages of these technologies could help lower the cost of solar heat and expand their potential applications in solar thermal technology. On the other hand, the high vacuum used as highly efficient thermal insulation has to be guaranteed during the solar collector lifetime (~25 years) in order to maintain high conversion efficiencies. Therefore, several tests have been performed since the startup of the solar plant in order to check that the performance of the solar field and of each of the solar collectors remain stable over time.

The Figure 7 shows the global daily plant production (heat injected into DHN) as a function of the daily global solar irradiation on the plan of array of the solar field for 2021 and 2022. This figure demonstrates that the performance of the solar plant remained unchanged since its startup. This graph also illustrates the ability of EFP to convert solar radiation into heat above 80°C with very high efficiencies from 45 (days with low irradiation) to 60% (days with high irradiation).

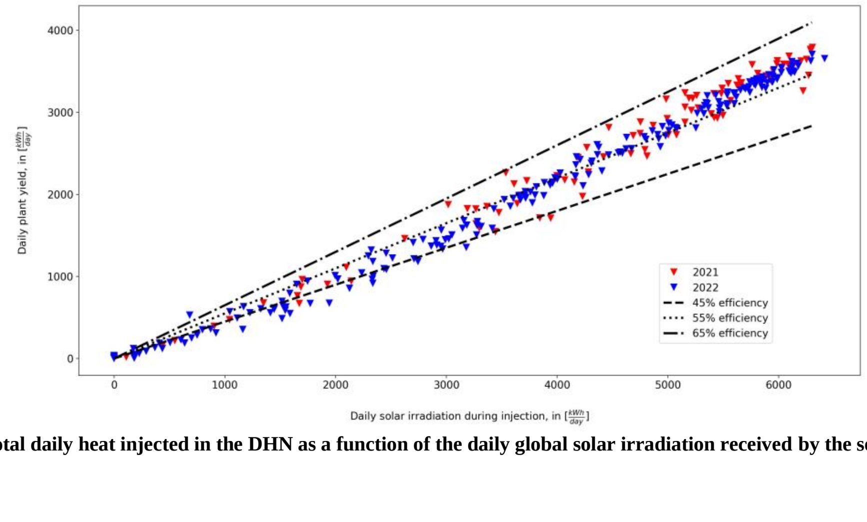
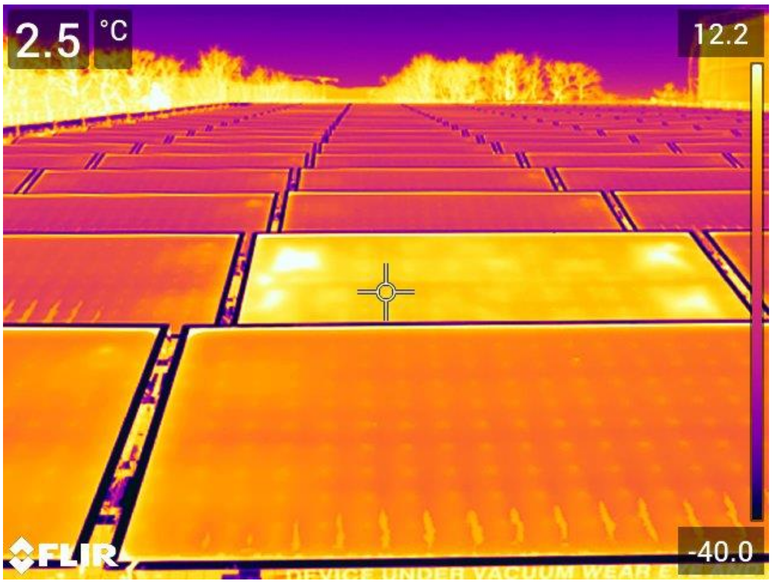


Fig. 7 Total daily heat injected in the DHN as a function of the daily global solar irradiation received by the solar field

In addition, the quality of the thermal insulation of each collector has been evaluated with an IR camera while the plant was in operation (see Figure 8). The objective of this test was to identify the collectors with higher surface temperatures. For each of the collectors with higher surface temperature, surface temperature was measured in the front and the back of the collectors at 11 different points. Two verification campaigns of the collectors were realized: one in January 2021 shortly after the commissioning of the plant and one in February 2022 after a year of operation. Eight collectors with higher surface temperature were identified. For those collectors the surface temperature is higher by 2°C in average compared to the other collectors. At this point of the project, it is not clear if the performances of those collectors have been significantly reduced or not. Additional investigations will be performed in 2023 in order to address this question. A new verification campaign will be repeated at the beginning of 2023 following the same procedure.

Fig. 8 IR Camera picture of the solar field showing one collector with higher surface temperature



6. Conclusions & perspectives

An 800m^2 solar plant using EFP from TVP Solar has been installed in Geneva and commissioned in January 2021. This plant is connected to the return of a large high temperature DHN. It is operating between 80°C and 90°C. Up to today, this plant is the largest solar plant using EFP technologies connected to a DHN. A monitoring system has been deployed in order to follow the plant performance and its stability over time. During the first year of monitoring, the plant has produced and injected 536MWh of heat in the DHN corresponding to a specific productivity of 684kWh/m^2/yr or 45% of conversion efficiency. This high productivity illustrates the advantage of EFP technology for application above 80°C and with a large share of low irradiance. This productivity is much higher than the state-of-the-art flat plate collector under similar conditions. Electrical COP of 53.5 and 37.5 were estimated for the solar field alone and the plant respectively. This COP could certainly be improved by reducing the pressure losses (tubes with larger diameter) and the pumps operating time.

In addition, the performance stability was studied at the solar field level and for each collector. For the first 18 months of operation, no performance degradation has been found at the solar field and at the collector scale. Nevertheless, 8 collectors with higher surface temperature were identified. At this stage of the project, it is not clear if the performance of those collectors is significantly reduced. Further investigation will be pursued in 2022 on this issue.

The performance monitoring of this plant will continue at least until 2024 with objective to study the stability and reliability of EFP from TVP Solar. In addition, a numerical model of the plant is being developed in Trnsys. This model will be validated using the data collected. The validated model will then be used to evaluate and compare various optimization measures to improve the plant performance (irradiance threshold for plant startup for example).

7. Acknowledgments

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9. Nomenclature

Abbreviations	**Signification**
η_{Sol}	Solar field efficiency [%]
η_{Tot}	Solar plant efficiency [%]
DHN	District Heating Network
DHW	Domestic Hot Water
E_{DHN}	Total solar heat injected yearly in the DHN [MWh]
EFP	Evacuated Flat Plate Solar Collector
E_{sol}	Total heat produced yearly by the solar field [MWh]
E_{Sol_poa}	Total solar irradiation received yearly by the solar field on the plan of array [MWh]
HEX	Plate Heat Exchanger
MWI	Municipal Waste Incineration Plant
$Flowrate_{CAD}$	Flowrate in the HEX on the DHN side (secondary) [m^3/h]
$Flowrate_{Field}$	Flowrate in the solar field [m^3/h]
$Flowrate_{HX}$	Flowrate in the HEX on the solar side (primary) [m^3/h]
GI_{poa}	Global Irradiance on the plan of array [W/m^2]
T_{Air}	Ambient air temperature [°C]
$T_{p,i,field}$	Solar field inlet temperature [°C]
$T_{p,o,field}$	Solar field outlet temperature [°C]
$T_{s,i,HX}$	Plate heat exchanger intlet tempreature on DHN side [°C]
$T_{s,o,HX}$	Plate heat exchanger outlet tempreature on DHN side [°C]