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Analysis of a medium temperature solar thermal installation with heat storage for industrial applications

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Abstract

Willing to be an active participant to the Swiss strategy for sustainable development, Colas Switzerland SA, has decided to integrate a solar thermal installation in one of its bitumen storage industrial site. Situated in Yverdon-les-Bains (Switzerland), the solar installation aims to provide up to 60% of the thermal energy demand of the site. Coupled with a gas boiler, the solar collectors were designed to meet the energy needs of an onsite building, and to ensure constant temperature of a bitumen tank and two emulsions tanks (mixture of bitumen and water).

In order to analyse and optimise the thermo-economic and environmental efficiency of this installation, a R&D project funded by the Swiss Federal Office of Energy was launched in 2014. This article gives an overview of the project objectives and describes the solar thermal installation and its operating modes. It also presents the numerical model and the first experimental results.

First observations have revealed a thermal installation operating well behind its expected targets. Typically, the solar collector efficiency at temperatures above 200°C is 50% lower than expected since it is operating under non-optimal conditions. Some technical dysfunctions have also been detected in the control system of one of the storage tanks. Consequently, a thorough evaluation of the operation of the installation was conducted to identify any other anomalies.

In parallel to this work, the numerical model of the installation was developed and is currently under validation against the ongoing experimental measurements. Preliminary simulations of the installation in its current state have showed a solar yield nearly 2 times lower than expected, confirming the existence of anomalies in the running of the installation.

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1. Introduction

The integration of solar heat in industrial processes is considered to have an important potential, but its development is still at the beginning as less than 1% of the installed solar thermal collectors worldwide are used for industrial applications [1]. In Europe, the share of the final energy consumption due to the industrial sector is around 26% [2] of which 67% is for heating purposes [3]. Moreover, 30% of the industrial process heat demand is in temperature range below 100°C which is very suitable for conventional, well-established solar thermal systems. Another 27% uses temperatures between 100 and 400°C [4] for which several new types of solar thermal collectors have recently been developed to reach high efficiency at these higher temperatures [5].

Within the framework of the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Task 49, 151 solar thermal installations supplying process heat were reported worldwide, with a total capacity of about 100 MW_{th}. [6] It is, therefore, very important to capitalize on this potential and promote this technology in industrial process heat where solar thermal systems can be a very competitive alternative to fossil fuels.

Bitumen and emulsion mixtures are used in the road construction sector which is an industry based on fossil energy. During the construction season in Europe (April to September) these products are constantly maintained at a temperature below 200°C and this generates an important heat consumption. Conscious of the important potential of the solar heat in its industrial process, but also of the economic and environmental issues related to fossil energy, Colas Switzerland has implemented high temperatures solar thermal systems to maintain its bitumen tanks above 160°C.

As a starting point, a pilot project was launched on Tecvia production site in Geneva (Switzerland) in 2011. This installation was designed to reduce energy consumption related to maintaining bitumen at constant temperature and implicitly, reduce emissions of greenhouse gases [7]. On the other side, simulations performed by Colas Switzerland showed that the annual performance of the solar thermal system could be significantly improved in particular by reducing the operating temperature and the distance between the collector field and the storage tanks.

Based on this experience, Colas Switzerland SA has developed a second solar thermal system with several changes and more flexibility which was installed at a bitumen storage site in Yverdon-les-Bains (Switzerland). In both installations high vacuum flat plate collectors were used [8].

During 2014, a R&D project funded by the Swiss Federal Office of Energy was started aiming to analyse and optimise the thermo-economic and environmental performance of this installation as well as to evaluate the performance of energy storage in the bitumen. A four years monitoring was also scheduled in order to perform a time evolution analysis of the system's efficiency.

Nomenclature

T _m	Mean temperature of the solar collector	[°C]
T _a	Ambient temperature	[°C]
G	Solar irradiation	[W/m ²]
x	Normalised collector temperature (T _m -T _a)/G	[Km ² /W]

2. System description

The site in Yverdon-les-Bains is used by Colas Switzerland to store bitumen and emulsion mixtures used for road construction in the nearby region. The products are delivered hot from the production plants and stored in three thermal insulated tanks: two for emulsion mixtures and one for bitumen. A fourth storage water tank is employed for storing low temperature energy for emulsion and to provide an onsite building with hot water for both sanitary purposes and space heating. This building is located next to the bitumen-emulsion storage facility, see Fig. 1.

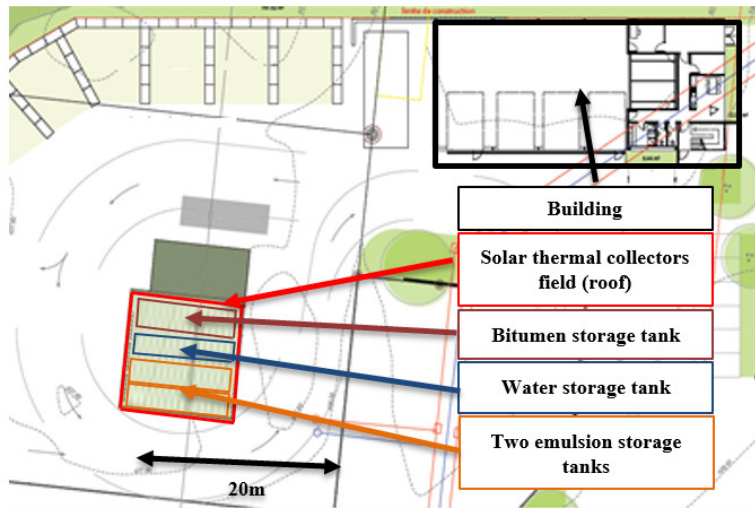


Fig. 1. Yverdon-les-Bains site plan with the solar field location

A high vacuum flat plate solar collector installation was designed to deliver heat at two different temperatures levels ranging from:

- 160 to 200°C for maintaining bitumen at temperature (depending on the bitumen stored);
- 50 to 90°C for maintaining emulsion at temperature or for building needs.

It is important to notice the good correspondence between the energy demand and the solar energy supply in this kind of application as the bitumen and emulsion are only used during the summer season, when solar energy is most available. Whenever the solar energy is not sufficient, a gas boiler provides full backup energy to the system.

2.1. Solar collectors

In the site of Yverdon-les-Bains, the solar thermal field consists of 35 solar collectors spread over 7 rows of 5 collectors in series that can deliver a peak power of 96.1 kW with a solar irradiation of 1000 W/m². They are placed on a specially designed metal frame above the storage tanks, with an orientation of 50° West and 20° tilt. The heat transfer fluid (HTF) used in the system is a Shell mineral oil of type Thermia B supporting over 300°C, without chemical or physical degradation [9].

The solar collectors were developed at the European Centre for Nuclear Research (CERN) and are manufactured by SRB Energy. The SRB Ultra High Vacuum (UHV) collector [8] uses a technology based on a flat plate collector that can be combined with various mirror structures, which are a cost-effective way to increase the aperture area and to improve performance at high temperatures. For this particular installation, the collector type c2 was chosen. For further information on the collectors characteristics and performance, please refer to [8].

These collectors are characterised by excellent thermal insulation provided by the high vacuum level (10⁻⁸ mbar at ambient temperature). The vacuum is achieved and maintained using a *Getter* pump which is activated by solar energy and it has the ability to remove any gas molecules inside the collector through chemical reaction. This insulation combined with solar concentration allows the solar collector to reach a stagnation temperature of 400°C, significantly greater than conventional solar thermal collectors. Moreover, compared to the "classic" concentration collectors that only use direct solar radiation, these collectors have the advantage to use a great part of the diffuse solar radiation, due to a larger absorber area. The average share of diffuse radiation in Switzerland is about 50%. [10].

2.2. Storage tanks

Four insulated storage tanks are present on the Yverdon-les-Bains site. Two of the tanks are used for emulsion storage, one for bitumen storage while the fourth is filled with water and serves as heat storage to meet the energy demand of the onsite building and of the emulsion. Each of the emulsion tanks has a volume of 50 m^3 and is integrated into a container. The water storage tank has a volume of 27 m^3 and the bitumen storage tank of 70 m^3 , see Fig. 2. All tanks are insulated with 200 mm stone wool.



Fig. 2: Three of the four storage tanks in the bitumen facility

For its storage process, Colas Switzerland SA requires solar heat at two temperature levels:

- between 60°C and 90°C for the water and emulsion tanks
- between 160°C and 200°C for the bitumen tank

2.3. Building

The building, built in 2012, comprises two parts: a mechanical workshop and an administrative part composed of two levels. The energy consumption of the building includes the space heat demand for the winter period and DHW demand for office employees and operating personnel for their daily showers. The building heating annual energy demand was estimated by Colas SA at $38'500 \text{ kWh}$. However, a more accurate determination of this consumption is necessary because the use of the mechanical workshop is not fully accounted. Measurements during this project are expected to demonstrate the relevance of this estimation.

2.4. Gas boiler

When solar energy is not available, the energy demand for the building or for the bituminous products is supplied by a gas boiler with a rated power of 250 kW . This boiler was installed in 2013.

The boiler contains an important thermal oil storage which gives a large thermal inertia to the boiler. Although this energy stock generates heat losses, the burner operates mostly at reduced power and provides better overall performance compared to the old oil boiler. In addition, the natural gas operation will reduce the system emissions of greenhouse gases.

2.5. System integration and regulation

The solar pump is switched on when the solar irradiation is larger than 300 W/m^2 . The HTF is recirculated through the solar collectors until the field temperature is above the storage tank temperature, see Fig. 3. In order to improve the solar collector's efficiency, solar heat is delivered in priority to the water tank - at lower temperature range. If the water storage tank has reached the set point temperature, then the solar energy is delivered to the bitumen tank.

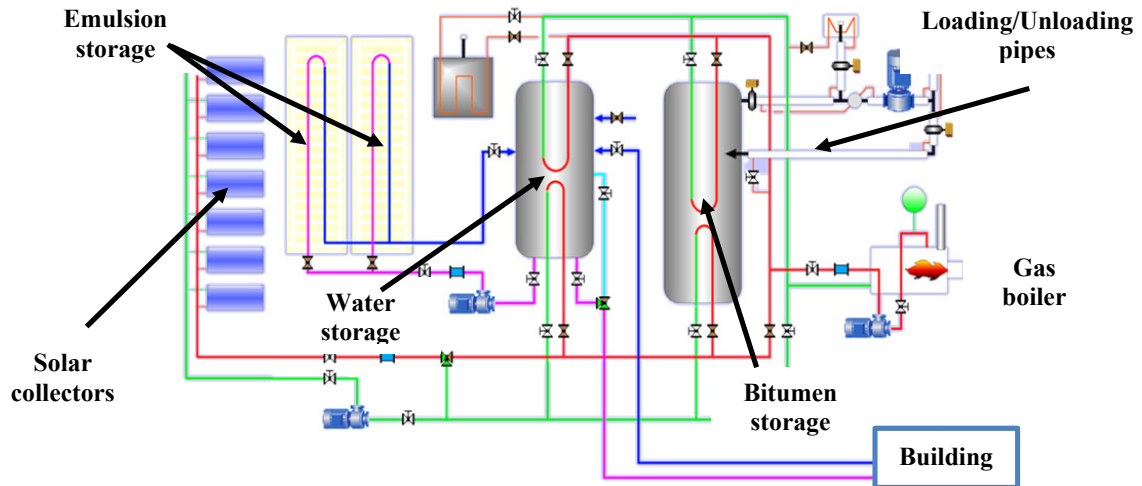


Fig. 3: Hydraulic scheme of Colas SA system in Yverdon-les-Bains.

To be noticed that the bitumen inflow and outflow pipes of the tank must always be kept at a temperature of 200°C by the gas boiler, to ensure a good consistent flow through loading and unloading of the tanks.

3. Experimental results

Refurbishment of the heating system was finished during March 2015 and therefore data measurements are only available from April onwards. For this reason, the period analysed in this article will only concern one road construction system from April to October 2015. The monthly solar radiation and mean ambient temperature for this period can be seen in Fig. 4.

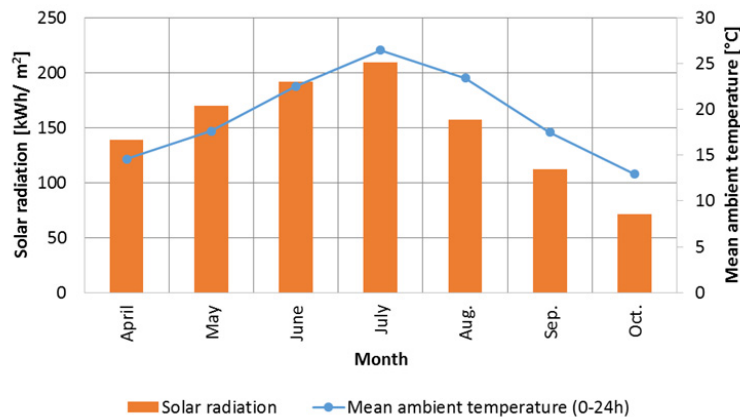


Fig. 4: Measured weather data for Yverdon-les-Bains from April to October 2015

3.1. Solar collector field

The solar collectors' performance during the summer season is very dependent on the overall heat consumption, in particular that used for the emulsion because it requires lower temperatures resulting in a better efficiency. Several problems were detected during 2015 on the emulsion heating system which affected significantly the solar yield.

One of the main dysfunction observed was an internal temperature sensor in one of the emulsion storage that displayed a non-representative value of the storage temperature. A manual blending of the product inside this storage tank revealed 18 K temperature rise (see Fig. 5) for the internal temperature which suggests that most likely, the position of this sensor was not appropriate.

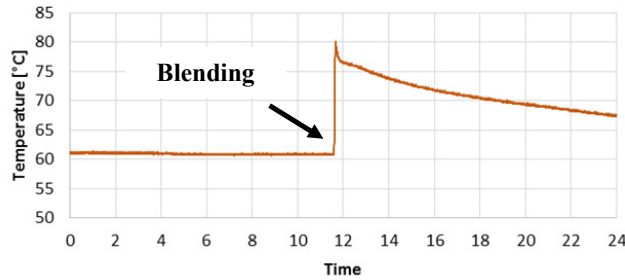


Fig. 5: Typical daily emulsion storage temperature during the summer season

Thus, the set point temperature for this storage tank was never reached which prevented the normal heating of the second emulsion tank with solar energy and ended being heated up only by auxiliary electric heaters. The repositioning of the sensor is scheduled for the end of the construction season, during the winter season 2015-2016.

Another dysfunction occurred during August and September when the emulsion heating circuit was filled with air, compromising the energy transfer from the water storage to the emulsion storage. This explains the drastic decrease in solar energy delivered to the water storage in August while the solar energy delivered to bitumen increased, Fig. 6.

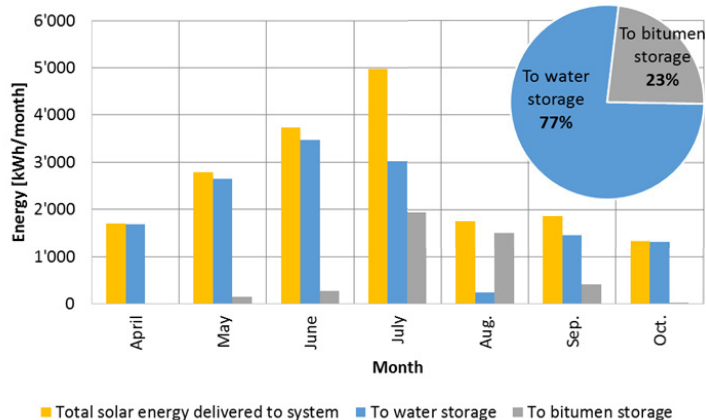


Fig. 6: Monthly solar energy delivered to the system

Nevertheless, the total solar energy in August has clearly decreased because the collector efficiency is much lower when operating above 200°C. Indeed, the theoretical efficiency of the collector should be 50% less when loading the bitumen storage when compared to loading the water storage. However, measurements show that when operating at high temperature, the efficiency is even lower than expected. Two days for each operating mode (water

storage loading and bitumen storage loading) were performed in order to compare with the theoretical curve of the collector, see Fig. 7.

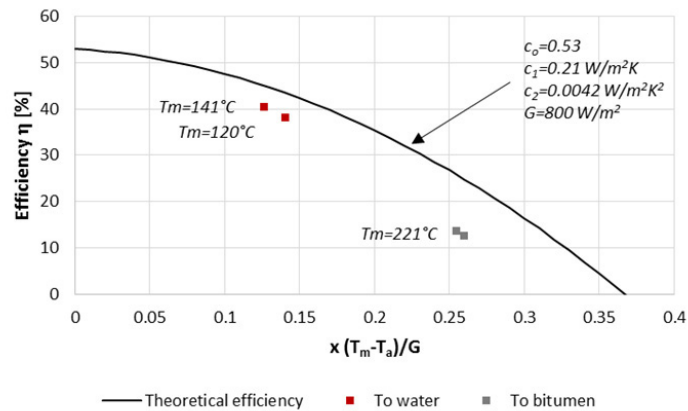
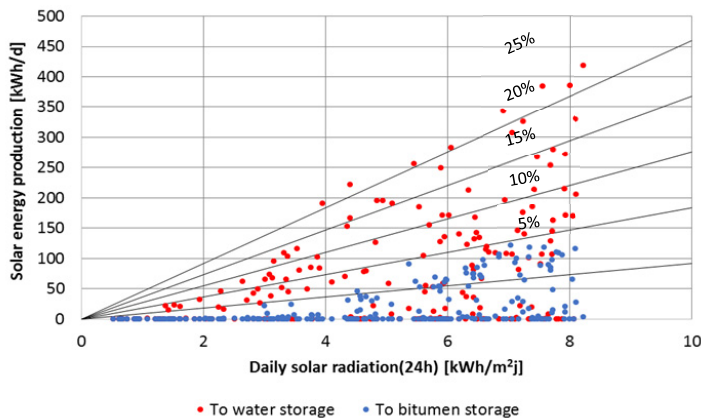


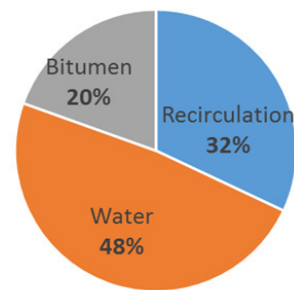
Fig. 7: Theoretical performance curve of the collector vs. measurements

For lower operating temperatures, only about 10% difference is observed which is expected taking into account the field measurements and thermal losses in the pipes between collectors. Still, when operating at 221°C an important difference of nearly 50% occurs when compared to the theoretical values. This can be explained by the fact that the collector's certifying tests were only performed up to 100°C temperature and with water as HTF. Extrapolations of values to higher temperatures seems to be inadequate in this case. Further investigations will be performed during this project to establish the correct behaviour.

The maximum daily solar yield was measured at 419 kWh with an efficiency of 27%. In Fig. 8a, a clear difference in solar collectors efficiency is observed when loading the water storage (red points) in comparison to loading the bitumen storage (blue points). Measurements at 0% efficiency correspond to days where the solar pump is on but the temperature needed for loading the storages is not reached.



a



b

Fig. 8: (a) Daily solar radiation and solar energy production; (b) Share of electricity consumption of the solar pump

This shows that the solar circuit control system must be improved in order to reduce the electricity consumption of the solar pump as in this configuration, one-third of the electricity is consumed for recirculating purposes, without delivering solar energy to the system, see Fig. 8 b.

A thermal picture of the solar field (see Fig. 9 a) was also taken and revealed that some solar collectors are colder than others most probably because vacuum is being lost and heat losses increase. This can also affect the global efficiency of the collector field.

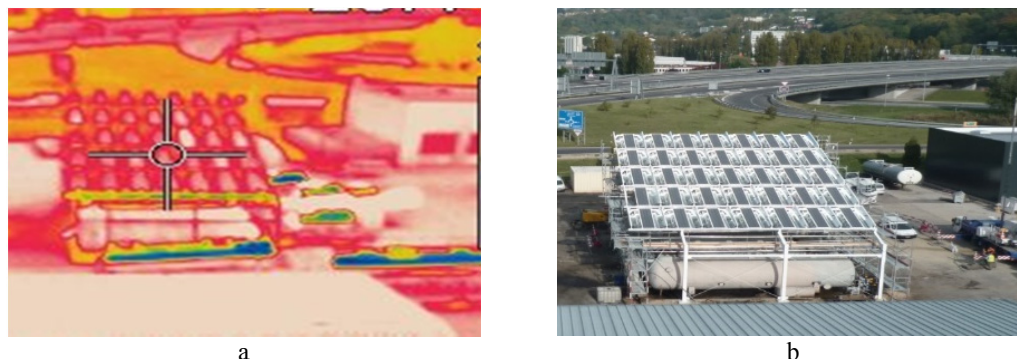


Fig. 9: (a) Thermal image of the solar collector field; (b) Image of the solar collector field

During 2015, Colas Switzerland activity in the region of Yverdon-les-Bains was higher than expected because of the renovation of a nearby highway. Moreover, the bitumen used in highways is a polymeric product which needs higher storing temperatures (close to 200°C). Consequently, the monthly solar fraction was quite low with a maximum of 25% reached in July. Only 12 days during the analysed period are found to exceed 50% solar fraction and 3 with more than 90% solar fraction.

3.2. Gas boiler

Given the relatively small solar fraction cited in the previous section, the gas boiler needs to supply a large amount of energy for the process. A positive point was that from July on, no energy was supplied by the gas boiler to the water storage. For the total period analysed, only 21% of the energy needed for water storage was delivered by the gas boiler. On the other hand, for the bitumen storage the findings are totally different as only 5% of the total energy needed is delivered by the solar collectors and 95% by the gas boiler.

Another interesting point was to find out that a substantial amount of heat loss comes from the bitumen circuit during loading and unloading of the tank. This circuit is only a few meters long, but is not well insulated despite being constantly heated (24h/7d) to keep temperatures above 200°C to ensure adequate flowing conditions of the bitumen.

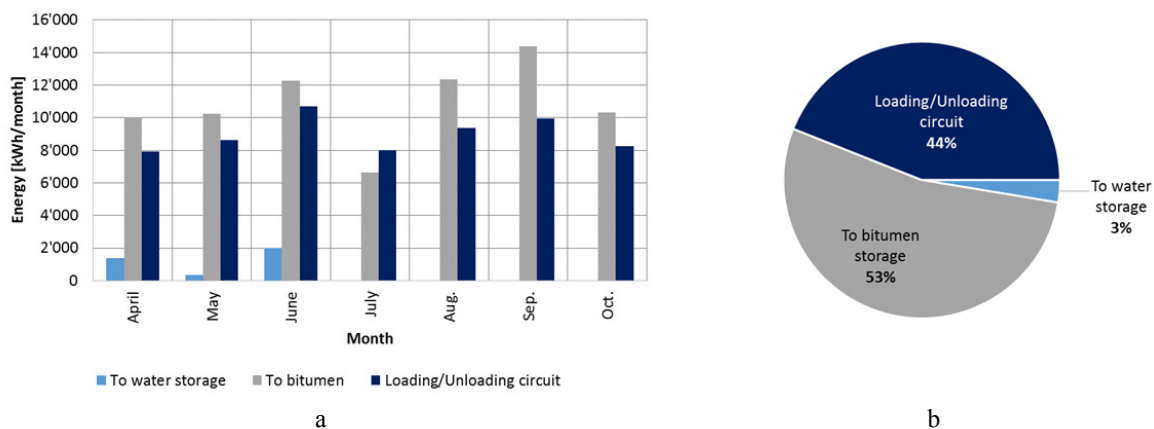


Fig. 10: (a) Gas boiler energy distribution; (b) Share of gas consumption

Several possibilities are now considered in order to reduce thermal losses in this circuit:

- Enhance insulation for the piping and especially of the opening valve which is currently not insulated at all;
- Better planning of bitumen loading and unloading to avoid continuously heating of the pipes;
- A combination of the first two solutions;
- Creating a new shorter loading/unloading circuit so that all piping and valves are located in an insulated box.

Beginning 2016, Colas Switzerland SA will decide which of these solutions is to be implemented. This will be followed by a set of measurements intended to evaluate the efficiency of the chosen solution.

4. Numerical model

A simplified numerical model of the heating system was designed with the simulation software Polysun [11]. The complexity of the installation prevents the use of any of the standard models of Polysun. Hence, a specific model was designed to reproduce the behaviour of the installation in Yverdon-les-Bains and to simulate its annual performance. This model will be further used in this project to optimise the regulation procedure of the solar thermal system. Fig. 11 gives an overview of the simulation model and its different components.

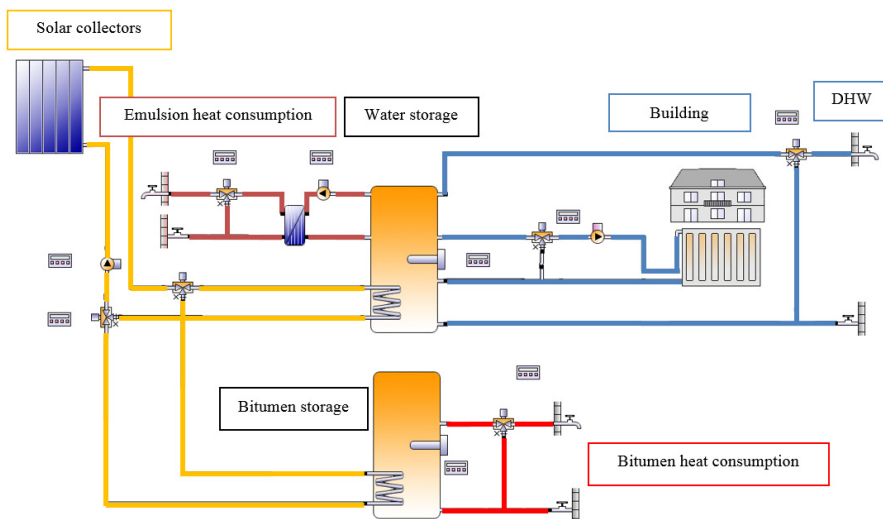


Fig. 11: Schematic diagram of the simulation model for COLAS installation in Yverdon-les-Bains.

4.1. Assumptions and simplifications

The collector model is not a standard component of the Polysun database and was provided by SRB Energy. The performance coefficients were estimated considering the experimental results for temperatures up to 100°C. Validation of the model for operating temperatures between 100°C and 400°C will be carried out. Bituminous products are considered as a first approach as thermal oil, which was the only fluid having thermal properties close to bitumen. This simplification will subsequently be adapted and validated with the measurements during the R&D project.

The annual energy demand for heating was taken as 38'500 kWh, according to Colas SA. The DHW consumption was calculated as 25 MJ/m² based on the Swiss standard SIA 380/1 [12]. With a gross floor area of 589 m², the annual DHW demand amounts to 4'100 kWh.

The modeling of the gas boiler and the hydraulic system related has been simplified. This element has been replaced with two integrated gas boilers placed within each of the two storage tanks (see Fig. 11). With this option, pump and piping components connecting the gas boiler to the storage tanks are not taken into account and this

should not significantly affect the total fuel consumption. However, thermal losses due to fluid transport and the gas boiler oil storage will be evaluated and later taken into account.

Polysun is not designed to deal with tanks that are not fully filled with fluid. Consequently, the energy consumed by the bitumen loading and unloading is simulated in a first approach as similar to a DHW loading profile. A constant inlet temperature is fixed while the outlet storage tank temperature is set to 160°C for bitumen and 60°C for emulsion.

First results show an annual solar yield of 22'360 kWh, but work is now underway to validate several subcomponents of the numerical model and certify this value. This will be followed by the validation against experimental results.

5. Conclusions

The potential of solar thermal systems in the industry has proven to be substantial and there is a growing need for reliable and cost-efficient systems in this area. This paper presents the integration of a medium temperature solar plant on an industrial site and the numerical modelling of this system. Solar energy was proven to be very suitable for road construction industry.

Preliminary measurements have shown the importance of the heat consumption for low exergy energy production systems like solar thermal collectors. Indeed, a dysfunction in the emulsion circuit reduced drastically the solar yield by forcing solar collectors to operate at higher temperatures and, consequently, at reduced efficiency. For the period considered in this study (April-October 2015) 18.2 MWh were supplied by the solar field to the system with a mean collector efficiency of 14% reported to the aperture area.

It was also highlighted that the solar collector efficiency at temperatures above 200°C is about 50% lower than expected. This decrease seems to be related to the extrapolation of values from measurements performed with operating temperatures up to 100°C. Further measurements and tests will be carried out in order to validate this assumption and to better understand the collector behaviour at high temperature levels.

A numerical model was set up with Polysun in order to represent the behaviour of the COLAS installation in Yverdon-les-Bains. Several assumptions and simplifications were necessary in order to correctly model this non-conventional system.

Simulation tool represents a powerful tool for plant sizing, optimization and energy yield estimations. It also allows to explore sensitivity analyses on different design parameters. First simulation results have shown annual specific collector yield of 128.5 kWh/m² aperture area despite the use of a very efficient solar thermal collector. This value is 1.8 times lower than initially evaluated by COLAS (238 kWh/m²a), but it is comparable to the Geneva installation results where a yearly solar productivity of 93 kWh/m² has been reported [7]. The solar thermal simulation is currently under validation against experimental results. Investigations proceed to evaluate all possible areas of improvement in order to maximise the solar yield and reduce gas consumption and implicitly greenhouse gas emissions for this industrial application.

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