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Analysis of a Solar Thermal Installation for Medium Temperature Industrial Applications

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Abstract

The analysis and optimisation of a medium temperature solar thermal installation for bitumen storage is presented in this article. Coupled with a gas boiler, a solar thermal installation was designed to provide heat to an onsite building, a bitumen tank and two bitumen emulsions tanks The behaviour and performance of this medium–temperature solar system for industrial process have been investigated based on measurements and simulations for subsequent optimisation of the process. A number of anomalies of the system have been identified, corrected and the impact on its performance evaluated. Results show that, on an annual basis, solar energy is mainly delivered to the water storage tanks. Simulations show that there is room for improvement and that the solar production could be roughly doubled if the system operates as designed. The life cycle impact assessment of the solar installation showed that the infrastructure impacts predominate over the entire life cycle. Environmental return on investment periods were found quite interesting in the case of an optimised solar bitumen storage system.

Keywords: *industrial application, solar thermal collectors, thermal storage, bitumen, simulation, measurements, LCA*

1. Introduction

In Europe, the industrial sector is responsible for 26% of the final energy consumption (Eurostat, 2013) which makes it an important player in the energy consumption and greenhouse gas emissions debate. Moreover, (Krummenacher and Muster, 2015) showed that 26% of the industrial process heat demand is lower than 100°C and 19% is between 100 and 400°C. A huge potential exists for these low to medium temperature heat demands to be delivered using existing conventional and advanced collector technologies. It is, therefore, very important to capitalise on this potential as today less than 0.1% of the heat demand in industry is supplied by solar energy (Mauthner and Weiss, 2015). The purpose of this study is to investigate the use of solar energy for bitumen and emulsion (mixture of water and bitumen) storage applications for a subsequent optimisation of the process.

Low temperature processes up to 100 °C are very suitable for using well-established conventional solar thermal systems. For processes in the medium temperature range up to 250 °C, several new types of collectors have been developed recently. Recently, within the framework of the International Energy Agency (IEA) Solar Heating and Cooling (SHC) Task 49 (IEA-SHC, 2014) 134 solar thermal installations supplying process heat were reported worldwide, with a total capacity of about 100 MW_{th} representing a very small fraction (less than 0.1%) of the total solar thermal capacity installed. Those figures demonstrate that there is a considerable untapped potential for solar thermal energy in the industrial sector.

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Bitumen and emulsions are used in road construction, an industry based on fossil energy with medium temperature heat demands. The operating temperature for bitumen emulsion ranges from 60 to 75°C while for bitumen it ranges from 160 to 200°C. These hot products must be stored, transported and used hot to maintain their workability. Conscious of the important potential of solar heating in the industrial context, but also of the economic and environmental issues related to fossil energy use, COLAS Switzerland, has implemented a medium temperature solar thermal system to maintain its bituminous products tanks at the required temperature.

A first pilot project was launched on an asphalt production site in Geneva in 2011. The solar thermal installation was designed to reduce energy consumption related to bitumen heating and implicitly, reduce emissions of greenhouse gases (Maranzana and Bornet, 2011). This first experience has shown the significant potential to cover the useful heat demand of bitumen heating. On the other side, simulations showed that the annual performance of the solar thermal system could be significantly improved with a better orientation and tilt, lower operating temperature or shorter distance between solar collectors and bitumen tanks. Based on this experience, COLAS Switzerland has integrated an improved and more flexible solar thermal system in its bitumen storage site in Yverdon-les-Bains (Switzerland). In both installations, the solar thermal heat was delivered using ultra high vacuum flat plate collectors.

This paper reports the findings of the R&D project funded by the Swiss Federal Office of Energy aimed to analyse and optimise the thermo-economic and environmental performance of this medium temperature solar thermal installation. (Bunea et al., 2013).

1.1 Description of the facility

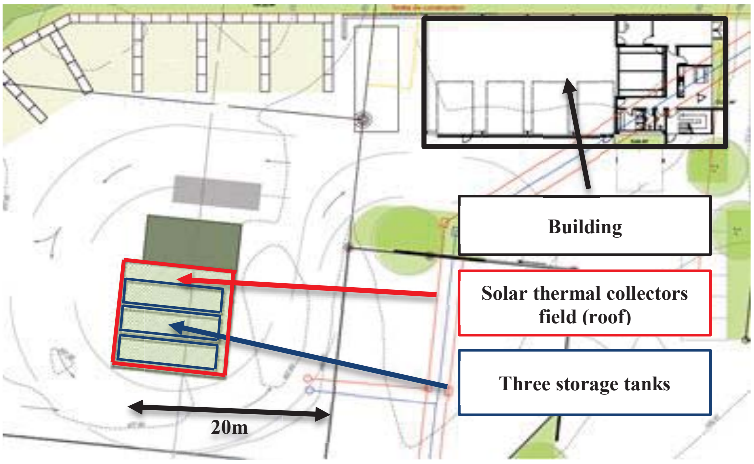

Fig. 1 : Bitumen storage site at Yverdon-les-Bains

In Yverdon-les-Bains, COLAS stores bitumen and its emulsions to be used in road construction. The products are delivered hot from the production plants and stored in three thermal insulated tanks. An ultra-high vacuum flat plate solar collector field backup by a gas boiler are used to heat the bituminous products to temperatures between 160 and 200°C for bitumen and between 60 and 75°C for emulsions. In addition, the heating system delivers energy for space heat and domestic hot water (DHW) for a building located next to the facility. Fig. 1 shows the location of the various components on the site.

There are two operating seasons:

- April to September: “Summer season” - bitumen and emulsions have to be permanently available at operating temperatures. Furthermore, DHW has to be provided to the office and workshop buildings on the site.
- October to March: “Winter season” - Bitumen or emulsions generally not stored, with an exception for dry winters where storage could be extended a few months. In the general case, only heat for space heating and DHW has to be provided.

1.2 Solar collectors

The solar thermal collectors are manufactured by SRB Energy and were developed at the European Centre for Nuclear Research (CERN). The SRB Ultra High Vacuum (UHV) collector (Benvenuti, 2013) uses a technology based on evacuated flat plate collectors. This collector can be combined with cylindrical mirrors, which are a cost-effective way to increase the aperture area and to improve performance at high temperatures.

These collectors are characterised by excellent thermal insulation provided by the ultra-high vacuum (10-8 mbar at ambient temperature) achieved and maintained using a Getter pump. This pump is activated by solar energy and it has the ability to remove air or any other 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 take also advantage of the diffuse solar radiation, due to a larger absorber area. In Switzerland, the diffuse radiation is an important part of global solar radiation, accounting for more than 50% in Yverdon-les-Bains (Bunea et al, 2013).

The solar thermal field in Yverdon-les-Bains consists of 35 SRB UHV Type C2 solar collectors spread over 7 rows of 5 collectors in series for a theoretical peak power of 96.1 kW with a solar irradiation of 1000W/m^2. 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.

1.3 Storage tanks

The bitumen storage site contains four insulated storage tanks, see Fig. 2. 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 building but also for emulsion operating needs. The water, emulsion and bitumen storage tanks have a capacity of 23, 50 and 70 m^3, respectively.

The water and bitumen storage heat demand is provided by solar energy and a backup gas boiler whenever solar energy is no available. Emulsion storages heat provision is either through the water storage by means of a heat exchanger or with electric heaters for night operation.

Fig. 2 : Storage tanks of the installation

The bitumen storage site was designed to store solar heat at two temperature levels:

- Water tank: between 60 °C and 90 °C depending on the weather conditions, but also on the building and emulsion heat demand.
- Bitumen tank: between 160 °C (for viscosity reasons) and 200 °C (thermochemical decomposition of bitumen beyond this temperature).

1.4 Building

The building was built in 2012 and comprises a mechanical workshop with a heated volume of about 1500 m^3 and offices over two floors with a total volume of ~1200 m^3.

The building annual heating demand was measured to be 42'370 kWh and includes space heating during winter and DHW for office employees and mechanics who take daily showers.

1.5 Gas Boiler

When solar energy is insufficient, heat provision for the building or to compensate the bitumen tanks losses is supplied by a 350 kW gas boiler. This backup system was installed in 2013 and replaces an old 1000 kW oil boiler.

The boiler contains an important thermal oil storage (~2000 l) 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.

1.6 System integration and regulation

The solar pump is switched on when the solar irradiation is larger than 300 W·m^{-2}. It circulates the HTF 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 priority to the water tank - at lower temperature range. If the water storage tank has reached the set point temperature, then the extra solar energy is delivered to the bitumen tank. Inflow and outflow pipes of the bitumen 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 periods.

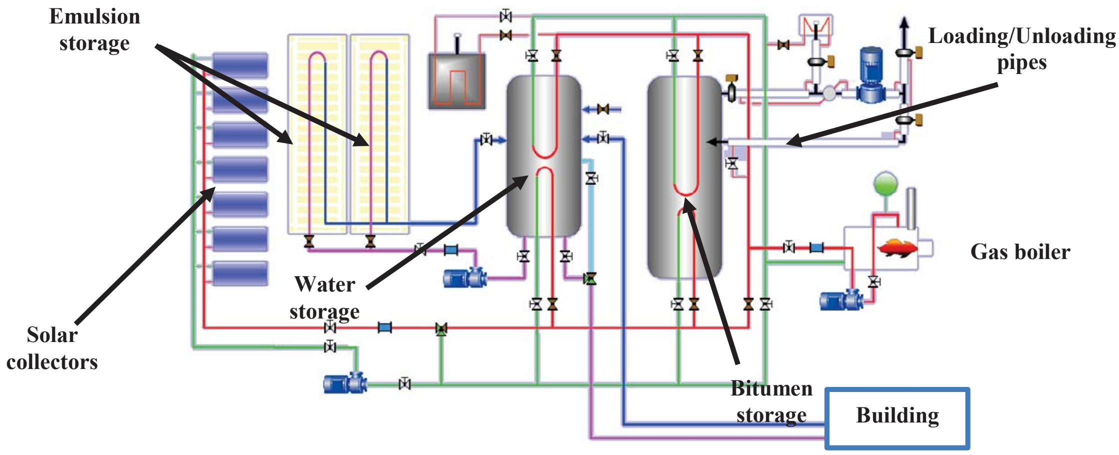

Fig. 3 : Schematic representation of the bitumen storage system.

2. Anomalies and failure analysis

In order to investigate the facility real behaviour and possible anomalies and failures to the expected operation, the facility was instrumented with sensors in the system lines to measure fluid temperatures and flow rates. Troubleshooting of this particular solar thermal system has revealed the following problems:

- The internal heat exchangers of the storage tanks are improperly sized, with a value 3 times lower when compared to the general rule of thumb (e.g. Jobin et al., 1994) for conventional solar collector applications. This causes performance of the system to be reduced.

- Estimation of the heat loss from tanks have shown that the insulation around the bitumen tank is probably improperly installed. For simulation purposes, the measured thermal insulation had to be reduced 10 times in order to have the same thermal loss as the measurements.

- Measurement of the collectors' efficiency have shown an important discrepancy between the accredited test values and the measured ones, see Fig. 4. Differences observed for the optical efficiency (15%) can be partly explained by eventual dust or bituminous particles deposits on the collector glasses and mirrors. A thermographic analysis of the solar collectors' field has further suggested that the thermal insulation of the UHV is also not fully ensured for some of the collectors. Consequently, global efficiency of the collector field is compromised, see Fig. 4. For high operating temperatures, the difference with the theoretical efficiency of the collector exceeds 50%. This highlights the fact that extrapolation of certified tests results beyond 100°C is not appropriate for evaluating these solar thermal collectors.

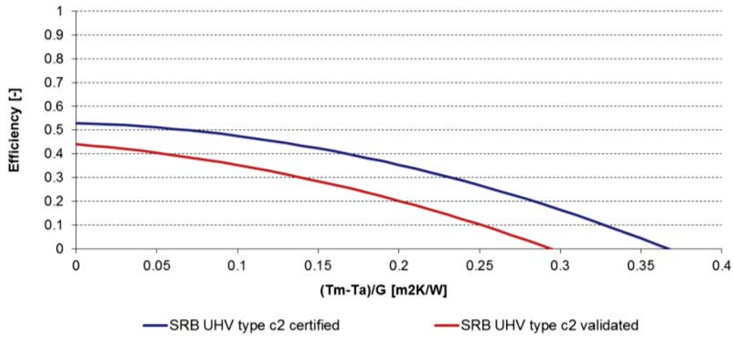

Fig. 4 : SRB UHV type C2 collector efficiency curve

3. Measurement campaign

The described system has been monitored continuously since 2014. This article presents the measurements performed between April 2015 and March 2016 following the modifications implemented from the preliminary study (Bunea et al., 2015). This period includes all improvements made to the system and a full year of measurements showing summer and winter periods.

Fig. 5 shows the weather conditions measured on the site during the investigated period (monthly values):

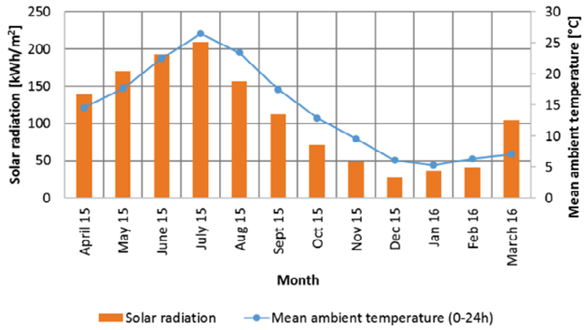

Fig. 5 : Monthly average solar radiation and ambient temperature for Yverdon-les.Bains from April 2015 to March 2016

Results for the period considered show an uncommon evolution during the year, see Fig. 6.

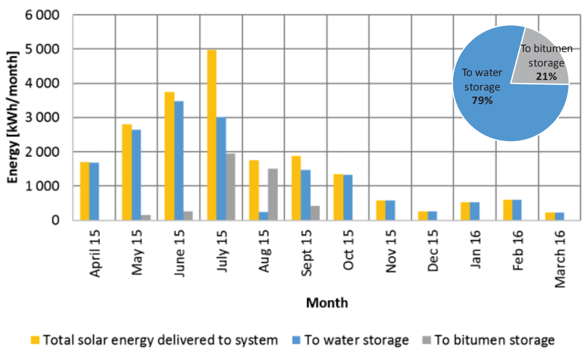

Fig. 6 : Monthly solar energy delivered to the system, 2015

From April to July, an increase almost linear of the solar energy production was observed, with a peak of about 5000 kWh in July. From August onwards, the total solar energy delivered to the system decreased substantially due to a hydraulic problem found in the water storage tank that was taken out of service for two months. Under this configuration, solar collectors delivered energy mainly to the bitumen storage, operating at higher temperatures, which greatly reduced the efficiency of the solar thermal system. The breakdown of solar energy delivered to the bitumen and the water storage tanks on an annual basis was found to be 21 and 79%, respectively.

During the winter season, it can also be seen that solar energy is only delivered to the water storage tank for space heating and DHW purposes. This amount of solar energy is, nevertheless, low because the combination of shorter days and more diffuse radiation (Yverdon-les-Bains tends to be often overcast) means less solar radiation than in the summer season.

Switzerland's 2015-2016 winter season was an exceptionally dry and warm winter. For this reason, road construction activities kept going beyond de normal summer season and storage of bitumen carried forward until December. The required energy for the bitumen storage site, in this exceptional period, was supplied by the backup gas boiler. Fig. 7 shows the breakdown of the thermal energy delivered to the water tank, bitumen tank and the bitumen loading/unloading circuit, this latter heated exclusively with the gas boiler.

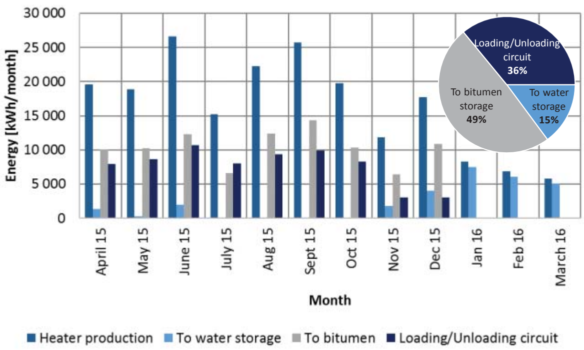

Fig. 7 : Breakdown of the energy delivered by the gas boiler

It can be seen that the gas boiler supplies energy to the water tank primarily during periods where bitumen is not stored. The maximum monthly energy from the gas boiler is found to be over 25000 kWh but the average monthly value for the summer season is about 20000 kWh. This value falls to about 10000 kWh in the winter period. The breakdown of energy delivered by the gas boiler shows that a significant part, 36%, is used to heat the bitumen loading/unloading circuit to enable sufficient fluidity and proper workability of the bitumen. Heating of the emulsion tanks were found to be 98% supplied by electricity and only 2% by the water tank.

Based on this information, it is possible to calculate the solar fraction of the installation, a key factor to evaluate the performance of the solar thermal system. The solar fraction is the ratio between the solar energy supplied to the water and bitumen tanks and the total energy required by the system, including gas and electricity energy consumptions.

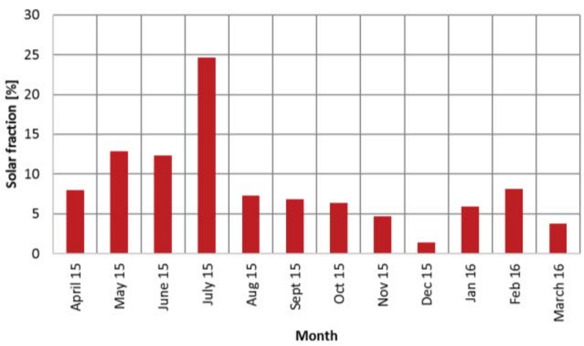

Fig. 8 : Average monthly solar fraction of the system

Fig. 8 presents the solar fraction of the installation on a monthly basis. It can be observed that for the entire year, solar fractions are generally quite low, with a majority less than 10%. The high value of ~25% solar fraction observed in July is due to the good climatic conditions, see Fig. 5, but also because of a low activity in the road surface construction sector and implicitly on the industrial site for this specific month.

The low values mean that for this particular application under current operating conditions, solar energy is not fully maximised. The operational problems encountered with the water tank in August have significantly contributed to this poor performance. However, an overall analyse of the system operation revealed a poorly use of the solar energy in the bitumen storage site to meet their specific energy saving goal. This is the case of the emulsion tanks that are mainly heated with electricity even when the water tank is able to provide the required energy. Furthermore, the real efficiency of the solar collectors was found to differ considerably from the theoretical values. Differences between these values are probably due to dirt accumulation on the glass cover and a potential vacuum loss, factors that were investigated in the simulation, see 4.2.

As the solar collectors supply energy to the water tank, their performance changes from that when energy is delivered to the bitumen tank due to their different operating temperature. To illustrate this Fig. 9 shows a comparison of the performances under these two supply configurations against the daily radiation.

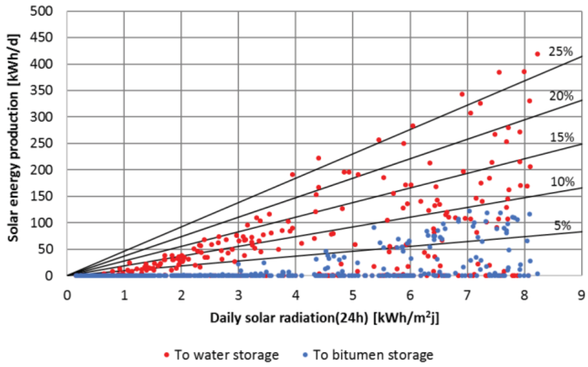

Fig. 9 : Performance distribution of solar collectors

Overall, the performance is low under all operating modes. The distributions indicate that the collectors' performance decrease when charging the bitumen tank (blue dots) with values below 10%. However, when delivering energy to the water tank (red dots) the performance is better and could reach 25%. In this case, scattering of the data is more pronounced because of the different utilisation modes of the water tank. Data points at 0% performance correspond to days where the collectors' pump was operating but no heat was delivered to any of the two tanks. This happens because the operating temperature is not higher than the storage tanks temperature. Consequently, 35% of the total energy used by the solar pump was spent for circulation only, clearly revealing a controller malfunction.

4. Numerical simulation

A simplified numerical model of the heating system was designed using the Polysun software, version 9.0.9. The complexity of the installation does not allow the use of Polysun current implemented models. 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 solar thermal control system. Fig. 10 gives an overview of the simulation model and its different components.

4.1 Assumptions and simplifications

The gas boiler and its hydraulic system were modelled as integrated gas boilers placed within the storage tanks (see Fig. 10). This means that the pump and piping components connecting the gas boiler to the storage tanks were not taken into account. However, thermal losses due to fluid transport and the gas boiler oil storage were considered.

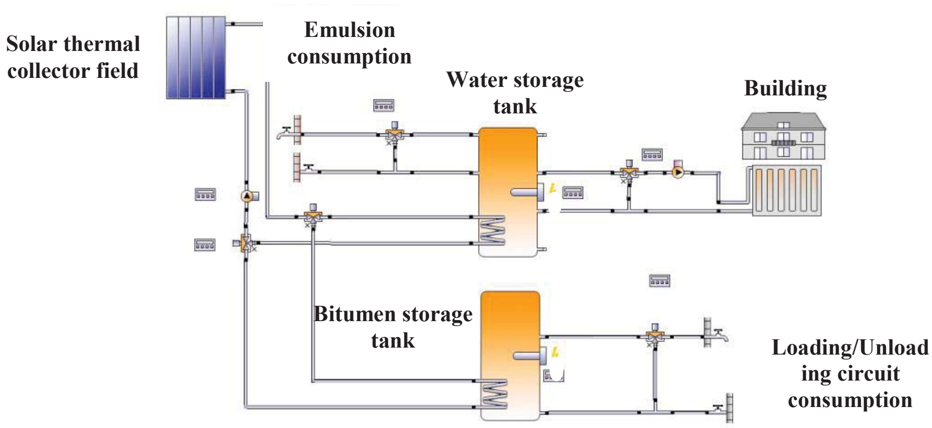

Fig. 10 : Schematic diagram of the simulation model of the bitumen storage installation in Yverdon-les-Bains.

Polysun is not designed to deal with tanks that are partially filled. Consequently, the energy consumed by the loading and unloading of emulsion and bitumen was taken similar to a DHW loading profile. A constant inlet temperature was fixed while the outlet storage tank temperature was set to 155°C for bitumen and 55°C for emulsion. The daily quantity of extracted fluid from the tanks was adapted in order to have the same amount of monthly energy consumption as measured for the given period. The electric heating elements for emulsion tanks were not included here, because in an ideal system, the emulsion should only be heated by the water tank.

Both storage tanks numerical models were validated against measurements taken when the tanks were turned off for several hours. This prevented any energy going in and out of the tanks, leaving heat loss from the tanks as the only driver. The collector model was provided by SRB Energy as it is not available in the Polysun database. The performance coefficients were estimated considering the certification test results.

4.2 Simulation results

To validate the overall operation of the system, measured monthly consumptions of the building, bitumen and emulsion tanks were introduced in Polysun. Fig. 11 compares the predictions of the annual energy consumption with the measurements and acceptable agreement is obtained. For the analysed period, heat supplied to the emulsion tanks was mainly by electricity. This working procedure leads to reduced energy consumption from the water storage in summer season and implicitly less solar energy production at lower temperatures.

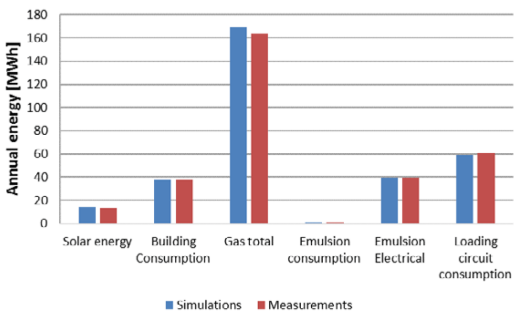

Fig. 11 : Simulated and measured annual energy flows

Based on the observed failures and improper operating practices, several simulations were performed to estimate the potential of this system operating under ideal conditions, namely: solar collector field performance as certified, well-insulated bitumen tank and improve control system operation. The latter allowing heat for emulsions to be supplied either by solar energy or by the gas boiler through the water storage.

Fig. 12 shows an increase of over 75% of the annual solar energy production when the collector performance is based on the certified values.

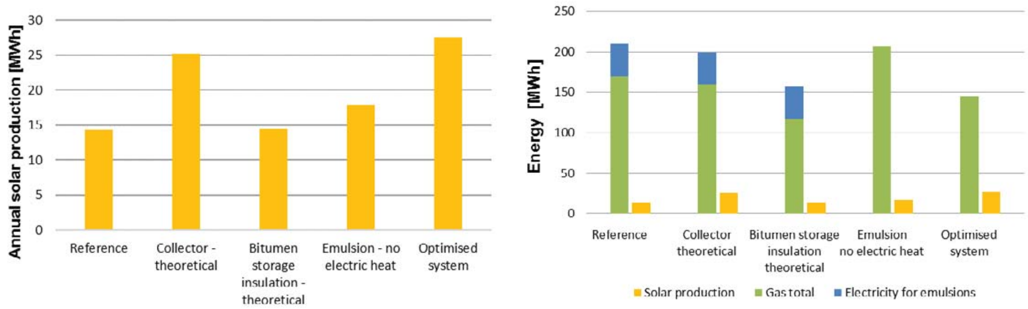

Fig. 12 : Predicted annual solar energy production and heat consumption for different system configurations

Improved insulation of the bitumen storage is found to have a significant impact on the gas consumption of the system (31%), but not on the solar production. The optimised system taking into considerations all enhancements presented above, while keeping the original heat demand, shows very promising results with an increase of over 90% for the solar energy production, no electric heating consumption and 15% less gas consumption when compared to the actual measured system. Nevertheless, in all cases, the overall share of solar energy contribution remains low (e.g. 19% for the optimised case).

The effect of different operating conditions on the performance of the optimised system was further investigated as a measure of the overall solar thermal efficiency. The effects of changing dimensions of the internal heat exchanger, collector field surface area as well as the collectors' orientation and tilt were studied, see Fig. 13.

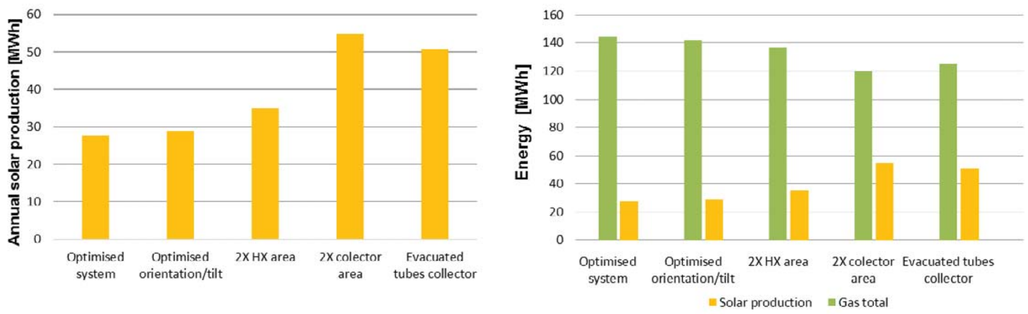

Fig. 13 : Predicted annual solar energy production and heat consumption for different operating conditions – optimised system

Collectors tilted 35°and south-oriented seem not to significantly increase solar production. In contrast, with larger heat transfer surface areas, high solar production is achieved due to a higher thermal performance of the heat exchangers and consequently lower inlet collector temperatures. Large solar thermal collector fields will certainly improve the annual solar energy production, but, because heat in summer is also supplied to the high temperature bitumen tank, collectors will present a low degree of efficiency.

As observed in Fig. 6, the large energy demand of the water storage results in a low solar energy supplied to the bitumen tank even with larger collector fields. The effect of replacing the SRB UVH C2 collectors by evacuated tube collectors for heating the water storage while bitumen was heated with gas revealed that it is possible to double the solar energy production while decreasing the gas consumption.

5. Life cycle analysis

An environmental assessment was conducted taking into account the environmental impacts of the installation materials as well as the energy consumed by the solar installation. The methodology applied in this study is conforming to standards ISO 14'040 series (ISO, 2006). The functional unit considered the impacts generated by the solar installation including the energy and materials consumption over an operational period of 20 years. The system boundaries include manufacturing and disposal of the materials used in the solar installation and the energy consumption throughout the use phase. Transport between the assembly site and the installation site is excluded from the analysis. All impact values were taken from KBOB database (KBOB, 2014) or Ecoinvent database v2.2 (Frischknecht et al., 2004). The indicators considered in this study are:

- *Cumulative Energy Demand NRE (CED_{NRE})* in MJ-eq considers non-renewable energy only. This indicator includes fossil, nuclear and biomass from primary forests (i.e. biomass consumption that contributes to deforestation or forest/woodland degradation)
- *Global Warming Potential (GWP)* in kg CO_2-eq

The analysis aims to estimate the environmental impact of the solar installation (solar collectors, pipework components and supporting structure) to compare to the potential energy savings it could possibly bring. Energy consumption of the installation was defined based on monthly simulations. The analyse considers the solar installation as operated between August 2015 and July 2016 (reference case) and the optimised system.

5.1 Impact of the solar installation

Data on material constituents of the solar installation, including the supporting structure of the solar collectors, was determined by the industrial partner or based on experience. Fig. 14 shows the environmental impacts of the main components of the solar installation. It can be seen that impacts due to the supporting structure predominate and are responsible for over 60% of the total CED_{NRE} impact because of the large number of components. Impact of solar collectors represent nearly 30% while pipework circuits 9%. A similar distribution is found for GWP indicator.

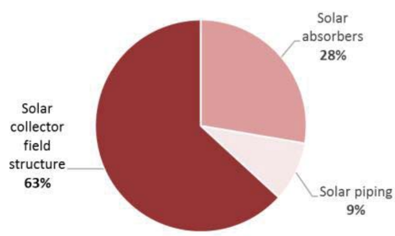

Fig. 14 : CED_{NRE} impact of main components of the solar installation

5.2 Assessment of the solar installation

The measurements and predictions have clearly demonstrated that the use of solar energy in bitumen storage can lead to energy savings. Thus, the solar energy used was converted into gas and electricity savings. Two cases were considered:

- Case 1: reference case where all supplied solar energy corresponds to gas savings as the emulsions were essentially electricity heated.
- Case 2: optimised installation according to simulations where all supplied solar energy corresponds to gas and electricity savings as the emulsions are only heated by the water storage.

In both cases, energy from the different pumps in the system (solar, boiler and emulsions) was taken into consideration.

The measured useful energy was converted into final energy by considering a thermal efficiency of 80% for the gas boiler (value from practice) and a 100% efficiency for conversion into electrical energy. The annual solar energy production for case 1 was predicted to be over 14000 kWh while for case 2 was above 27500 kWh. Fig. 15 shows the impacts of the solar installation due to infrastructure components and pump electricity consumption and the gas and electricity savings that could be made over the entire life cycle span.

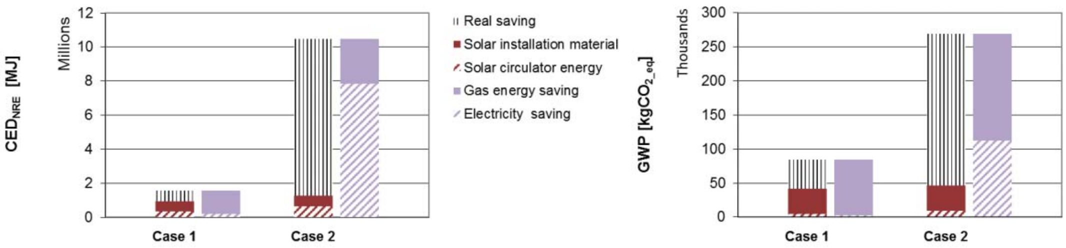

Fig. 15 : CED$_{NRE}$ and GWP impacts of the solar installation and derived real savings

In both cases and for both indicators, the solar installation related impacts are lower than the derived savings of primary energy or emissions of greenhouse gases. This means that the use of solar thermal for this particular application is still interesting in terms of energy savings despite the strong impacts of the supporting structure.

An important difference of impacts is also observed between case 1 and case 2. Indeed, the operating problems observed during the investigated period strongly penalise case 1. In the optimise configuration (case 2), replacing emulsions electric heating by the water heating, contributes to significantly increase energy savings and consequently, decrease impacts.

The evolution of these impacts and potential savings over time has allowed defining the return on the investment this solar installation offers, see Fig. 16.

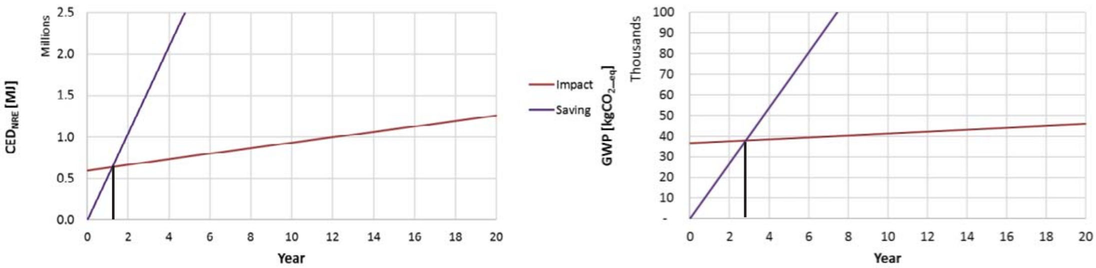

Fig. 16 : Return on investment for case 2

It can be seen that for case 2, the solar installation offers 1 and 3 years return on investment for CED$_{NRE}$ and GWP, respectively. Longer return on investment times, approximately 10 years, were found for case 1. Thus, improving the bitumen storage system and in particular replacing emulsions electricity heating by gas and solar is not only environmental but economically interesting.

6. Conclusion

The behaviour and performance of a medium–temperature solar industrial process for bitumen storage have been investigated based on measurements and simulations for subsequent optimisation of the process. Important differences, up to 50% at 220°C, between the certified performances of the solar thermal collectors and measured were observed during this project. The low solar fractions (~10%) observed for this installation are a result of combining low and medium temperature applications with a variety of operating modes into a single solar installation.

Simulations show that there is room for improvement and that the solar production could be roughly doubled if the system operates as designed. Furthermore, simulations prove that the heat exchangers designed for both thermal storages are undersized. Increasing solar collector area results in higher solar productivity, but still relatively low annual collector field efficiency.

Supplying water storage with solar energy from evacuated tubes collectors for emulsions and building heating needs, proved to be a cost-effective configuration for this industrial site.

The life cycle impact assessment of the solar installation showed that the infrastructure impacts predominate over the entire life cycle, accounting for over 60% of the total CED_{NRE}. Energy savings brought along by the solar installation more than compensate the additional material and energy related impact of integrating such a system. Less than 3 years environmental return on investment periods were found in the case of an optimised solar bitumen storage system.

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