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Solar assisted production of expanded polystyrene with high efficiency flat plate collectors

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Abstract

The use of solar thermal energy for process heating in industry is a young field which has a high theoretical potential to reduce the consumption of fossil fuel, but also represents a high technical and economical challenge. In the framework of a running project we investigate the integration of a solar heating system into an existing production process of expanded polystyrene (EPS), through utilization of recently developed high efficiency flat plate collectors. For this purpose a detailed process analysis based on an extensive measuring campaign and a simulation study with different solar integration and efficiency strategies are conducted. The results should provide a basis for the development of a suitable integration concept. This paper features the results of the analysis and of the simulation study, showing different solutions for solar integration with reductions of fossil fuel consumption up to 11 %.

Keywords: *Process heat, high efficiency flat plate collector, industry, expanded polystyrene, EPS, efficiency*

1. Introduction

The use of solar thermal energy to support industrial processes is a young field which has a high theoretical potential to reduce the consumption of fossil fuel, but also represents a high technical and economical challenge.

In the context of a R&D project, which is supported by the Deutsche Bundesstiftung Umwelt (DBU) and in cooperation with the industrial partners Solvis GmbH and Kluth Dachbaustoffe GmbH we analyse the use of solar heat for the production of expanded polystyrene (EPS).

According to a first estimation based on market data (Sprengard et al., 2013) and extrapolated consumption data the current annual heat demand of the entire EPS-plants in Germany is around 150 – 200 GWh/a and will increase due to a rising market. This energy is required as process heat at temperature levels between 40 °C and 110 °C. The annual course of production, which depends on the typically seasonal intensity of activities at the building sites, shows a minimum in the winter months. These two aspects represent good prerequisites for the use of low-temperature solar heat.

The aim of the project is to develop suitable solar integration concepts for EPS-plants with new high efficiency flat plate collectors. These spectrally selective, double glazed collectors were developed in the context of a completed research project (Föste et al., 2013). In order to improve their cost effectiveness the size is increased (from 2 m² to 8 m²) and design modifications are implemented.

The article focuses on the integration of solar heat into the EPS-production process and on energy efficiency measures based on the existing plant configuration of the Kluth Dachbaustoffe company. After a detailed analyses of the production process, the plant is modeled with the simulation software TRNSYS and a simulation study with various kinds of system optimization and sizes of the solar system as well as different control strategies is carried out. The results provide a decision basis for the solar integration concept and for the system dimensioning.

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2. Analysis of the production process

In this section the foaming process of EPS is explained. Figure 1 shows the simplified process scheme of the production line.

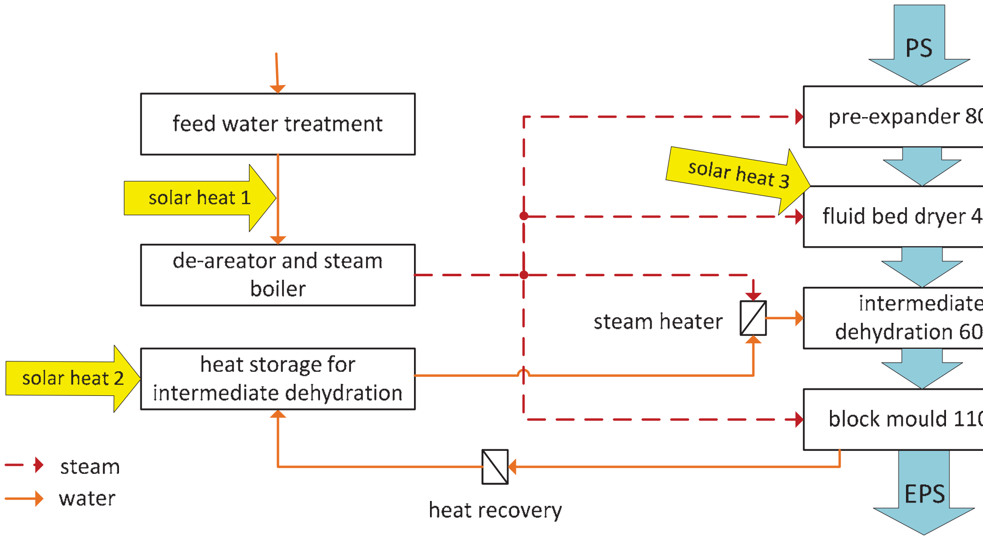

Figure 1: Simplified scheme of the foaming process and suggested integration points for solar heat.

The initial material is polystyrene granulate (PS), which contains of the main component polystyrene and the foaming agent pentane (Demacsek, 2016). This granulate first gets expanded in the pre-expander by steam at a temperature of around 80 °C, where it experiences a volume increase by about 5000 %. In the next step the pre-expanded and still in loose form existing polystyrene particles are pre-dried in the fluid bed dryer, which operates with steam heated air. Afterwards the EPS is stored in the intermediate dehydration. During the dehydration process the humidity, which has entered with the steam, is evaporated out to stabilise the EPS. Furthermore for the following processes the content of pentane has to be decreased to a defined percentage. The intermediate dehydration takes place in large silos and operates with an airflow heated by warm water from a heat storage tank (volume: 6 m^3)[1]. This water gets thermal energy from a heat recovery of the block mould and, if necessary, receives an additional re-heating from a steam heater before it supplies the dehydration-process. In the current plant configuration the re-heating is conducted without a control strategy and the temperature in the silos ranges between 25 °C and 85 °C. According to the statement of the plant operator a provided dehydration temperature of around 60 °C would be optimal for a high quality product. When the material is ready for the next process, it is foamed in the block mould to blocks of 6 m^3. The block mould operates with steam at a temperature of 110 °C. The EPS-blocks are then stored in a warehouse for further drying before they get cut and finished.

The production process runs during the day from Monday to Friday. The daily production time depends upon the seasonal demand, featuring a minimum during wintertime and a maximum in the late summer and in autumn. At night and on weekends there is no production. The yearly operation time amounts to approximatly 1000 hours. Currently the whole process plant of the company is supplied with heat from steam, generated by a natural gas-fired boiler. The annual energy demand of the boiler is about 1.6 GWh/a, the production volume is around 110.000 m^3 EPS per year.

Following a pre-analysis of the production plant, an extensive measurement campaign has been started in July 2015, focusing on analysing the detail of heat flows and temperature levels at single plant sections. Through the data analysis three potential integration points for solar heat have been identified: the preheating of feed water before entering the boiler (solar heat 1), the intermediate dehydration (solar heat 2) and the fluid bed dryer (solar heat 3). These integration points are chosen because of their temperature levels (below 100 °C) and the fact, that steam is not directly needed as a process component.

To verify the potential for energy efficiency measures, additional measurements have been carried out. The waste

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[1] The heating of the intermediate dehydration process is a specific feature of the considered EPS-plant.

heat flow of the pre-expander, the occurring condensate, waste heat from vacuum pumps and process-related radiant waste heat have been investigated. With the exception of the vacuum pumps, all analysed heat sources have a relatively low heat amount and/or a quite low temperature level making an useful and effective integration into the production process hardly possible. The cooling water of the heat pumps, which has an average temperature level around 50 °C at a flow rate about 7.2 m³/h and operates parallel to the block mould (circa 1000 h/a), is therefore taken into further consideration as heat recovery source. Additionally, the hydraulic interconnections of the single components were analysed with the aim of improving the process efficiency by considering the temperature levels of the available heat. This approach applies particularly to the heat recovery of the block mould and the intermediate dehydration.

3. Modelling the production plant

In order to evaluate the potential and possibilities of the considered efficiency measures and the implementation of the solar integration points in more detail, the relevant processes are modelled with the simulation software TRNSYS and a simulation study is carried out. Figure 2 shows the modelled components as well as their hydraulic interconnection schematically.

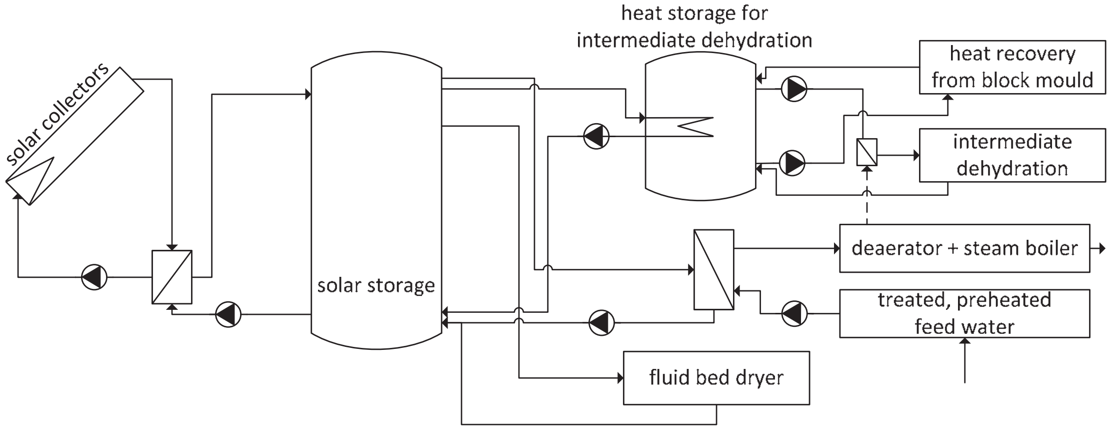

Figure 2: Schematic representation of the basic TRNSYS model for the current plant configuration supported by a solar thermal system.

The following components of the plant are modelled:

- Feed water supply (treated and pre-preheated by further heat recovery)
- Steam boiler
- Intermediate dehydration + associated steam heater
- Hot water tank for supplying the intermediate dehydration
- Heat recovery from the block mould (including the operation mode of the block mould)
- Fluid bed dryer

The single components are modelled considering the annual load profiles based on the measurement analysis.

The model for the solar thermal system includes the highly efficient solar collectors, a solar heat storage with an external heat exchanger for solar charging, a heat exchanger for pre-heating the feed water and a hydraulic connection between the solar storage and the heat storage for the intermediate dehydration.

Based on this model different simulation variations are calculated. Following parameters are varied:

- Solar system specific parameters:
  - Collector field area (given consideration of the available roof area)
  - Slope of the collectors
  - Construction of the collectors with its characteristic performance values
  - Volume of solar heat storage
  - Arrangement of the hydraulic connections at the heat storage
- Production plant specific parameters:
  - Hydraulic integration of the solar process heat

- Control strategy of the intermediate dehydration and its steam heater
- Hydraulic arrangement of system components (intermediate dehydration, heat recovery from the block mould)

4. Simulation results

The discussion is limited to the most significant findings of the simulation study. For the solar integration points, the following results are considered:

- Control strategies for the intermediate dehydration
- Integration of solar heat
  - Impacts of the hydraulic arrangement of intermediate dehydration and heat recovery: parallel connection vs. series connection
  - Integration of an additional heat recovery

All of the configurations are examined with different sizes of the solar thermal system. The collector parameters represent a highly efficient flat plate collector with spectrally selective air-filled double glazing (eta0 = 0.799, a1 = 2.45 W/m²/K, a2 = 0.101 W/m²/K², slope of the roof: 10 °).

4.1 Control strategies for the intermediate dehydration

As previously mentioned, in the current plant configuration the steam heater, which is responsible for the inlet temperature of the intermediate dehydration, runs uncontrolled. In order to ensure a high product quality, the ideal inlet temperature for the dehydration process is approximately 60 °C. Under this assumption, different control strategies are modeled and evaluated. Two exemplar configurations are considered here: System 1 - required temperature of 55 °C with continuous operation; System 2 - required temperature of 60 °C operating parallel to the plant operation.

The most significant differences of these two control strategies are shown in Figure 3.

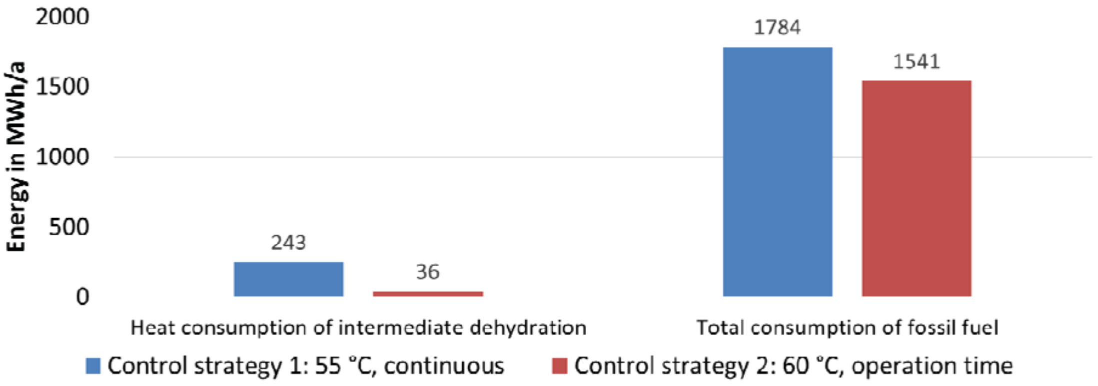

Figure 3: Calculated energy consumptions of the intermediate dehydration and in total for the considered control strategies without solar heat supply.

The energy consumption of the intermediate dehydration of system 1 is about 6 times higher than in system 2, mainly due to the different operation times. System 1 runs all over the year (except during the winter break), system 2 runs just about 1000 h/a, so nearly one-eighth of system 1. Because of the steam heater efficiency, the difference of 243 MWh/a between the total energy consumptions is a little higher than between the dehydration consumptions of 207 MWh/a.

To which extend the quality improvement of the product can compensate the significant increase of the energy demand, can only be evaluated by the plant operator on the basis of a comprehensive economic assessment.

In the following investigations both control strategies are considered. Since control strategy 2 has a lower heat demand for the intermediate dehydration, the control takes in case of available solar heat an additional heating for the dehydration beyond the operating periods into account.

4.2 Integration of solar heat

As previously mentioned, three solar integration points are considered. Based on the measured data of the current plant configuration, first estimations concerning the range of solar heat integration potential are done.

The theoretical potential for the feed water pre-heating (integration point 1) is defined by the temperature limitation in the solar storage tank, which amounts to 90 °C. On the assumption that the feed water can be pre-heated over the course of the year to 90 °C, the fossil energy savings are around 7 %. With the assumption that solar heat substitutes the complete supply of the steam heater, the theoretical solar heat integration potential of the intermediate dehydration (integration point 2) for the uncontrolled operation in the current plant configuration is about 8 %.

The estimated heat demand of the fluid bed dryer, therefore its maximum potential for the usage of solar heat is about 4 %. The current configuration features a heat exchange with steam supply. To ensure a sufficient heat supply by warm water laborious modifications of the existing supply system are necessary. Thus a solar heat supply for the fluid bed dryer is not taken into consideration for our simulations.

4.2.1 Impacts of the hydraulic arrangement of intermediate dehydration and heat recovery

In the current plant configuration the intermediate dehydration and the heat recovery from the block mould are parallel connected to the heat storage. To figure out if a series connection is more efficient than the existing one, both configurations are simulated, as shown in Figure 4.

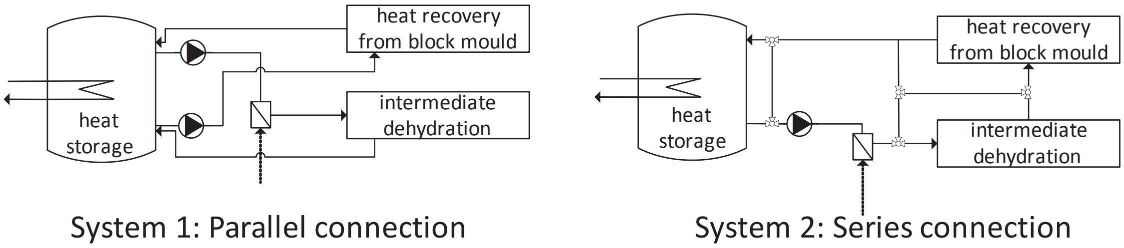

Figure 4: Sketch of the two different system configurations.

The simulation results for control strategy 1 and 2 are shown in Figure 5. The graph illustrates the reductions of fossil fuel as well as the additional heat supply of the intermediate dehydration for control strategy 2. The energy amounts are calculated in reference to the existing parallel plant configuration without the use of solar heat.

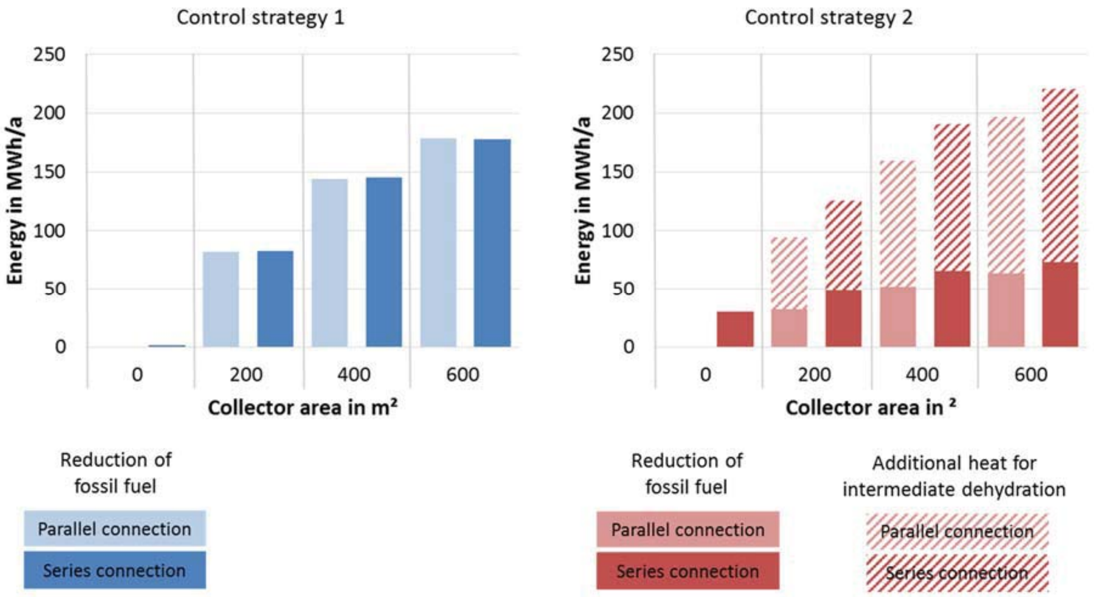

Figure 5: Calculated reduction of fossil fuel by changing the parallel connection into a series connection depending on the size of the solar thermal system.

As Figure 5 shows, for control strategy 1 the kind of interconnection has an insignificant impact on the consumption of fossil fuel. The main reason is that the system can take advantage of the series connection only when the two components are operating simultaneously. This occurs during approximately 12 % of the dehydration time, since the heat recovery only runs 1000 h/a. As a result most of the time the intermediate dehydration operates directly from and into the heat storage. Consequently there are no useful advantages with the change of this interconnection for control strategy 1.

On the contrary, for control strategy 2 a series connection leads to significant savings of fossil energy, due to a more efficient use of temperature levels of the available heat: The fluid, cooled down by the intermediate dehydration moves directly into the heat recovery where it can absorb more thermal energy at a lower temperature. Through a bypass these energy gains can be used directly for the intermediate dehydration. Compared to the parallel interconnection where the intermediate dehydration is supplied by a lower temperature from the heat storage, this series connection needs less steam for re-heating. This results in a significant reduction of fossil fuel. The difference of energy savings decreases by increasing the amount of solar energy production (size of the solar energy system). With a higher amount of solar energy the temperature of the heat storage in both systems rises. Therefore the advantage of using the heat recovery output directly for the dehydration decreases. Solar energy and heat recovery are partially in competition with each other.

The change from a parallel to a series hydraulic interconnection represents an energetically reasonable approach for control strategy 2 and is assumed for both strategies in the further simulation study.

In the next step, the theoretical maxima of fossil energy savings by the use of solar heat are calculated. For the feed water pre-heating fossil energy savings for both control strategies about 7 % of total energy demand were calculated, the same result as mentioned in the previous section. The fossil savings potential by heating the intermediate dehydration depends significantly on the control strategy. For control strategy 1 that results in a fossil energy reduction of 16 %, for strategy 2 in a reduction of 2 %. The theoretical total energy savings potential is about 23 % for control strategy 1 and about 9 % for control strategy 2.

The following figures present the achieved reductions of fossil fuel and the solar heat gains with collector fields up to 600 m² and as a function of the solar storage volume. Figure 6 shows the results for control strategy 1, Figure 7 for strategy 2.

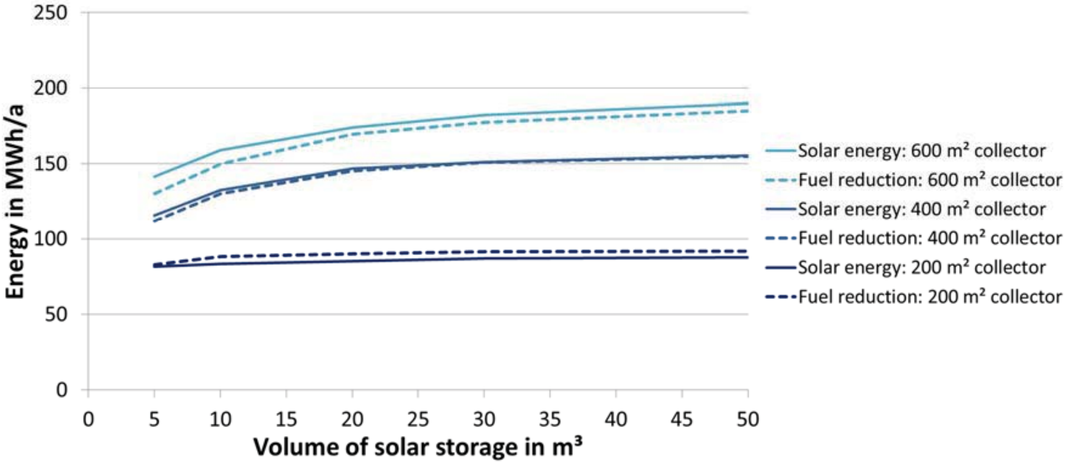

Figure 6: Control strategy 1: Calculated solar energy gains and fossil fuel reductions depending on collector area and storage volume.

Depending on the dimensions of the solar thermal system, control strategy 1 achieves solar gains up to 190 MWh/a. This corresponds to savings of fossil fuel up to 11 %. The amounts of solar heat gains and reductions of fossil fuel are approximately equal. The small deviations result from the boiler efficiency and heat losses of the solar thermal system. On the contrary, the results for control strategy 2 show significant differences between solar gains and fossil fuel savings. While the total solar gains are up to 200 MWh/a, the reductions of fossil fuel consumption reaches just 75 MWh/a, which correspondents to about 5 % of the total energy demand. The remaining solar heat gains up to 125 MWh/a are used to increase the process temperature for the intermediate dehydration, beyond the operation times, which is supposed to improve the quality of the EPS.

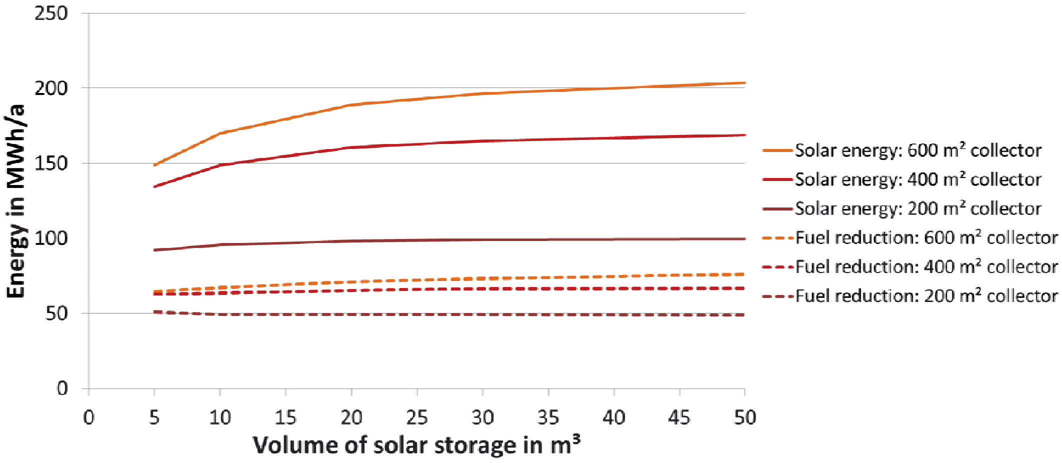

Figure 7: Control strategy 2: Calculated solar energy gains and fossil fuel reductions depending on collector area and storage volume.

Compared to the calculated theoretical fossil fuel savings potentials by the use of solar heat, control strategy 1 reaches 48 % with a collector field area of 600 m² and control strategy 2 reaches, at the same collector field size, 55 % of the potential energy savings.

4.2.2 Integration of waste heat from the vacuum pumps

As already noted, the cooling water of the block mould vacuum pumps could be used as a source for heat recovery. To analyse if this energy can be integrated usefully into the process, we carry out additional simulations. In the simulation model we assume that the heat from the recovery moves directly into the solar storage. Therefore, the potential heat sinks are the pre-heating of the feed water and the intermediate dehydration.

Figure 8 shows the savings of fossil fuel by heat recovery from the vacuum pumps for both control strategies and with different sizes of a solar thermal system with refer to the configuration without heat recovery and without solar heating supply.

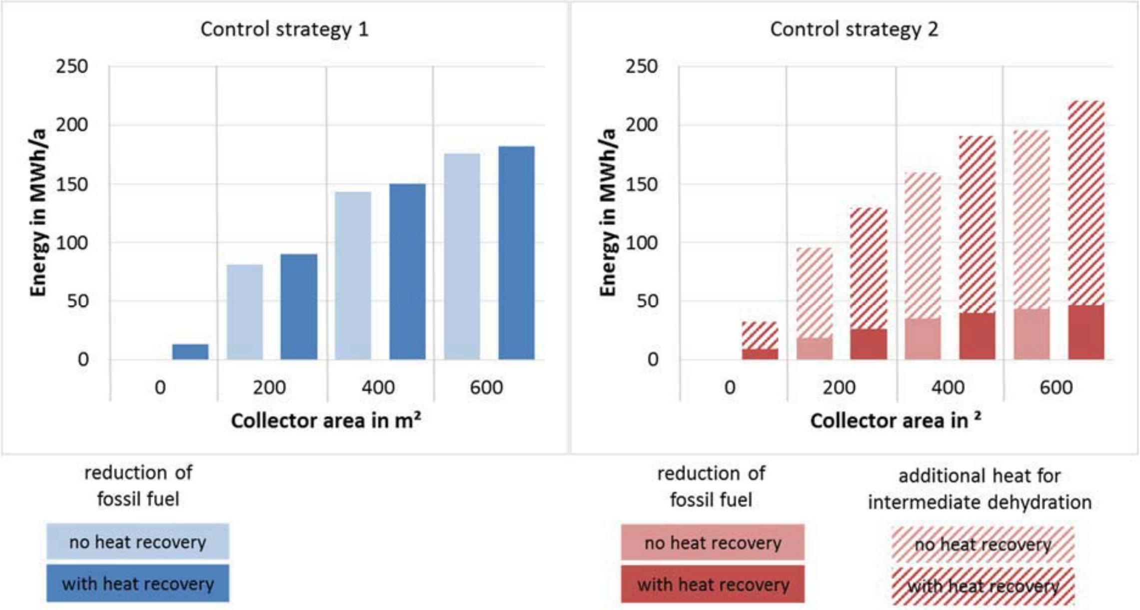

Figure 8: Calculated reductions of fossil fuel by using the heat recovery from the vacuum pumps depending on the control strategy and the solar thermal system.

The use of the heat recovery without a solar supply leads to fossil fuel reductions of 13 MWh/a and 9 MWh/a. The reason for the higher fuel reductions within system 1 is the higher energy demand for the dehydration and, thus, for pre-heating the feed water. In control strategy 2 additional heat for dehydration is available. In the dehydration downtimes, when the steam heater is not operating, recovered heat even at relatively low temperatures can be used for the dehydration process. The amount of recovered heat decreases by an increasing solar heat supply. Consequently the use of solar energy and the recovered heat are partially in competition with each other.

To assess the reasonableness of this measure economic aspects should also be taken into consideration.

The final decision of which plant configuration is more appropriate to save fuel and to optimize the product quality has to be made by the EPS plant operator. For this purpose and also for dimensioning the solar plant an economical assessment and an analysis of the product properties should be carried out.

5. Conclusion and Outlook

We carried out a simulation study based on experimental data from a real plant to analyse the potential of solar heating for assisting the production of EPS. According to our simulation results, combining energy efficiency measures with the use of solar energy at the investigated EPS plant provide a potential for fossil fuel reduction up to 11 % are possible. The pre-heating of the feed water and the intermediate dehydration are identified as suitable heat sinks. The fluid bed dryer operates at a low temperature and could be qualified for solar assistance as well. The practical implementation requires a laborious modification of the existing supply system and was not taken into consideration for our analysis.

In the next step, both the solar system integration as well as the heat recovery measures should be evaluated under economic aspects.

The results should provide a basis for developing a solar integration concept for EPS-plants. The final aim of the research is not only to evaluate the suitability of solar process heating within this specific production facility but also to assess the transferability of the results to the broad EPS-industry.

6. Acknowledgements

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