How to Combine a Solar Heating Plant and a CHP Most Efficiently for Industrial Applications?

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Abstract

To successfully decarbonize the industrial heat demand efficient solutions to reduce the CO_2-emissions of the industrial heat supply are required. Since solar heating plants usually cannot supply a company's low temperature heat demand, they must be combined with other low carbon technologies. Combined heat and power plants represent one of the most efficient technologies for generating heat and electricity from fossil fuels. In the future, CHP plants fueled by H_2 or biogas can be an important component of sector coupling. Nevertheless, the operation of CHP plants with fossil fuels causes CO_2 emissions, and renewable fuels are scarce. Therefore, a combination with e.g. solar thermal is recommended in order to reduce the operating hours. This study analyzes the combination of solar heating plants and CHPs based on TRNSYS simulations. Variations of the hydraulics, system design and operation, as well as control, result in an optimized system design considering the diverse industrial boundary conditions. The assessment is performed considering a technical evaluation. This work is conducted within the framework of IEA SHC Task 64/IV Subtask A.

Keywords: Solar heating plant, SHIP, CHP, TNRSYS, Task 64/IV

1. Introduction

The decarbonization of industrial heat demand is a huge challenge world-wide. In contrast to the higher temperature level above 200 °C, the low- and medium-temperature heat demand is suitable to be provided with solar collectors also in regions with lower direct normal irradiation. However, recent studies of the authors highlight two aspects that underline the importance of efficient hybrid heat concepts. Firstly, industrial heat demand is not constant throughout the year, but ambient temperature dependent heat plays a significant but often underestimated role in industry (Jesper et al., 2021). Consequently, the potential solar fractions are also in industrial application often limited by the seasonality of the heat load profile as it is usual in residential applications. Secondly, the availability of roof area is a strongly limiting factor in various industries, especially in the sectors with a high summer heat demand and a correspondingly high solar collector area potential (Pag et al., 2022). The VDI guideline 3988 (Association of German Engineers, 2020) is an established pre-design methodology for solar process heat plants in European countries. Here, the solar thermal system is designed with respect to the summer heat demand as key design parameter following the idea, to fully cover this heat demand on a sunny summer day. Consequently, only little solar excess heat is generated, but only comparably small solar fractions are possible if the summer heat demand is significantly smaller than winter heat demand. With respect to the climate change mitigation goals and in order to massively reduce the CO_2-emissions, solar heating plants have to be combined with other renewable or least most efficient technologies. Currently, there is not enough renewable electricity to cover world-wide heat demand with heat pumps. In addition, there is not always a suitable heat source for heat pumps and ambient heat is only available at a low temperature level with respect to the temperature requirements in industry. CHP are one of the most efficient solutions to use fossil fuels. Fueled with H_2 or biogas, CHP can play an important role for sector coupling or in regions with a very heat demand density (e.g. industrial companies). Therefore, also efficient combined heat and power (CHP) modules in combination with solar heating plants can be a solution to reduce CO_2-emissions if there are integrated efficiently. However, design guidelines and detailed information on how to combine both technologies are rare. In this study, an efficient system design and operation of solar heating plants and CHPs is defined with respect to different boundary

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conditions. Different hydraulics, design-strategies, and operation modes are compared employing TRNSYS (Klein, 2017) simulations, whose results are evaluated technically.

2. TRNSYS Simulation Models

In order to analyze how to combine solar heating plants and CHPs most efficiently, two different hydraulics are implemented in TRNSYS (Fig. 1). The first system follows the idea of "keeping it simple". Both technologies charge one shared buffer storage which supplies the heat for the process. In the second system, each of the technologies charges an independent storage. The storages are discharged alternating: if there is enough solar heat available, the solar buffer storage is discharged with priority; otherwise, if at the top the solar storage the process set temperature is not reached, the heat is supplied from the CHP storage. In both cases, the solar heating plants is operated with a set temperature control with variable flows in the primary and secondary circuit to always provide the set temperature if enough irradiation is available. The CHP efficiency is modelled with characteristic curves, calculating the thermal and electrical efficiency based on the net power and the part load ratio. The CHP is controlled with respect to the temperatures of the respective storage. Different switch-off criteria for the CHP are analyzed in the one-storage system allowing the CHP less (only top 10 %) or more (up to 60 %) usage of the storage by varying the position of the respective temperature sensor. In the two-storage system, the CHP starts operation if the top temperature of "its" storage falls below the set temperature and stops operation if the storage is fully loaded. Furthermore, the CHP has a minimum runtime of one hour and a standby time of 0.5 hours reducing interval operation.

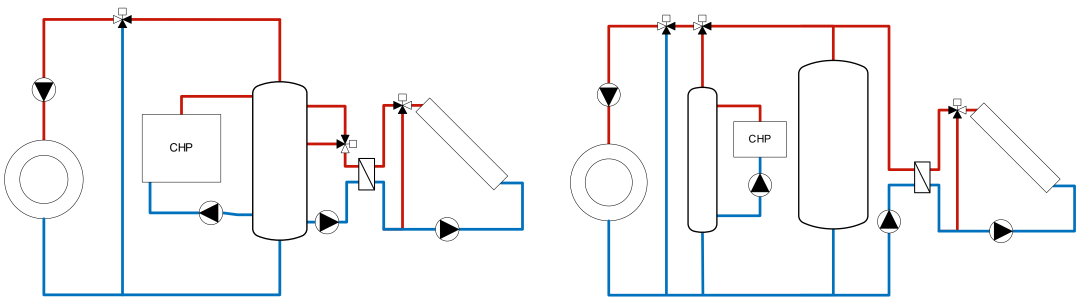

Fig. 1 Scheme of the two simulated hydraulics, left: one-storage system, charged by both solar collectors and CHP, right: solar collectors and CHP charge the corresponding storages independently.

3. Pre-design of simulation cases

To evaluate the system design and performance with different boundary conditions, the reference profiles from Jesper et al. (2021) are used. The respective regression profiles are shown in Fig. 2, (a) representing the profiles for working days and (b) for weekend days as well as holidays. Each of the profiles represents a different ambient temperature dependency (cluster) and the profiles for weekdays and weekend days can be combined as needed. In the further work, the combination of these cluster profiles is represented by the following nomenclature (working day cluster, weekend day cluster). According to the most often cluster combinations given by Jesper et al. (2021) the following cluster combinations are selected: (0,0), (0,1), (1,2), (2,3), (3,4). Potsdam, Germany, is chosen as location and the respective temperature profile is used to calculate the actual heat load profile. The annual heat demand is varied between 1, 3, and 5 GWh/a which is relevant for scaling effects on the one hand and for the thermal and electrical efficiency curves of the CHP modules. The process temperatures are set to 80 °C for the flow stream and 60 °C for return, which is typical for low temperature process heat (Lauterbach et al. 2012; Brunner et al. 2012).

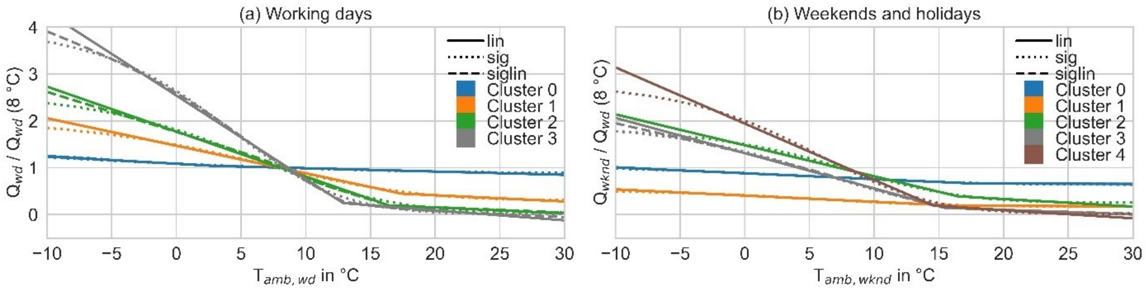

Fig. 2: Heat load profile regressions as a function of the ambient temperature from (Jesper et al., 2021)

The solar heating plant is designed according to the VDI guideline 3988. The collector area is sized to fully cover the summer heat demand of a standard production day on a good summer day in combination with a buffer storage. Consequently, solar excess heat is avoided to improve economics. Consequently, only low solar fractions can be reached (Pag et al., 2022), especially by companies with a significant ambient temperature dependency of the heat load and by companies with a limited roof area. For each of the four heat load profiles, the CHP is designed with various net capacities considering different full load hours (3000 to 7000 full load hours) in a year. Typically, this is done based on a sorted load curve. Therefore, the annual solar yield is estimated based on the load profile and the VDI guideline. Then, the solar yield is distributed in an hourly resolution employing the efficiency curve of the collector. Based on this, the residual heat load is calculated, and the CHP size is determined according to a given full load hour value. For the given cases, the CHP net electrical power varies between 50 and 300 kW_{el}. For the one-storage system, the storage size is determined with respect to the collector area based on the VDI recommendations. The same is done for the solar storage in the two-storage system; however, the CHP storage is sized to buffer one hour of full capacity operation of the CHP without heat demand.

4. Comparison of system performance of one- and two-storage system

To compare the technical performance of a one-storage system with a two-storage system, the system design shown in Tab. 1 is used.

Tab. 1: Parameters of the system design to compare one- and two-storage system

Parameter	Value
Solar collector size	1,660 m^2_{gr}
Solar storage	166 m^3 (100 l/m^2_{gr})
CHP capacity	422 kW_{th}, 324 kW_{el}
CHP storage size	18 m^3
Working day cluster	1
Weekend day cluster	2
Annual Heat Demand	3 GWh

Fig. 3 shows the difference between the one- and the two-storage system for several parameters. Consequently, the storage losses (*Q_loss,st*) are higher in the two-storage system as a second storage is installed which is only fed by the CHP unit. In contrast, the solar yield (*Q_sol,st*), calculated as the solar heat which is fed into the storage, is higher in the one-storage system compared to the two-storage system. This can be explained by the fact the storage is discharged continuously, so the mean bottom storage temperature throughout the year is lower compared to the two-storage system. Here, the solar storage is discharged discontinuously (only if the top of the storage reaches the set temperature) and only when discharged “cold” return water is fed into the storage at the bottom. Due to higher storage losses and less solar yield, more heat has to be provided by the CHP (*Q_CHP*, +1 %) in the two-storage system. Nonetheless, also slightly less heat is provided by solar heating plant and CHP compared to the one-storage system (*Q_load,covered* -1 %).

To sum up, with respect to an efficient system design, the one-storage system offers a more efficient system performance and should be preferred if a system is built from scratch. Apparently, the efficiency of the solar thermal system is not affected by the CHP unit which feeds into the same storage.

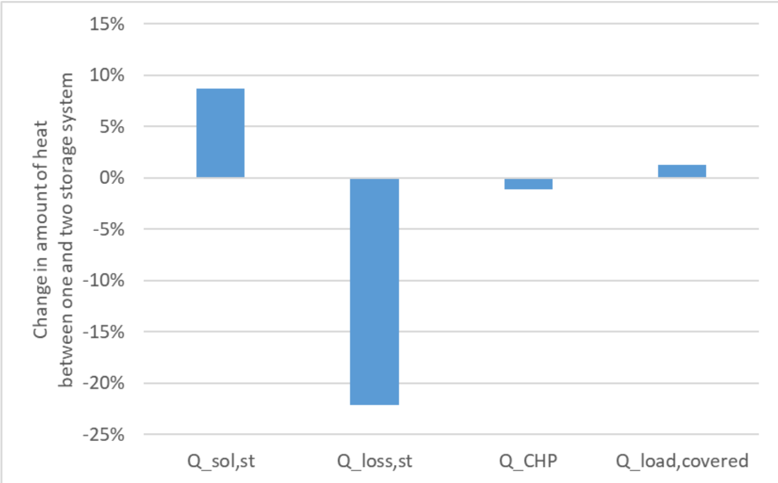

Fig. 3: Comparison of the one- and two-storage system for the selected system design

5. Technical performance of different system designs with the one-storage system

The results presented in section 4 highlight that a combined storage of solar heating plant and CHP is beneficial for the overall system performance. The efficiency of the solar heating plant is not significantly affected by the CHP. This can be explained by the fact that the CHP is only allowed to charge the top 10 % of the storage whereas the rest of the storage is only charged by the solar heating plant. With respect to the CHP this might lead to undesirable side effects, such as continuous switch-on and switch-off operation. As indicated in section 2, further simulations are done, analyzing the system performance if the CHP is allowed to heat up a higher share of the storage (top 30 % and top 60 %). Furthermore, the system performance is analyzed for the different load profiles. Fig. 4 shows the results for the different system simulations as a function of the full load hours of the CHP (inversely proportional to CHP capacity) exemplarily with an annual heat demand of 1 GWh/a – (a) showing the respective solar yield and (b) the starts of the CHP per year. Apparently, the heat load profile has a slight influence on the solar yield which is mainly due to a lower heat demand on week-end compared to production days (cluster (0,1), (2,3), and (3,4)). Furthermore, the capacity of the CHP does not show a clear influence on the solar yield, but only for cluster (0,1). Here, with higher CHP full load hours which is correlated with a lower CHP capacity, the solar yield is increasing. This might be an effect of the minimum run time of the CHP which is set to one hour. The higher the capacity of the CHP the more the storage is heated up which reduces the solar yield by higher storage temperatures. This is most significant for cluster (0,1) as the week-end heat load is especially low in comparison to the production day heat load here. The results show that the more the CHP is allowed to heat the storage, the more the solar yield decreases. Whereas the difference between the placement of the CHP control node, which stops the CHP operation if the set temperature is reached here, at 10 (blue) or 30 % (orange) of the storage height does not significantly affect the solar yield. allowing the CHP to heat up to 60 % of the storage decreases the solar yield by up to 10 %. This effect is stronger, if the heat load is more seasonal (cluster (2,3) and (3,4)) or if the CHP capacity is high. Fig. 4 (b) analyzes the number of CHP starts with the same variations. The influence of the position of the CHP control node is even stronger here. By allowing the CHP up to 60 % of the storage, the number of starts can be significantly reduced, partially up to 80 %. The influence of the CHP capacity and the seasonality of the load profile only shows a minor importance. The effect on economics can be hardly numbered, but it is common sense, that a smoother operation of CHPs with less starts has a positive effect on maintenance costs and lifetime.

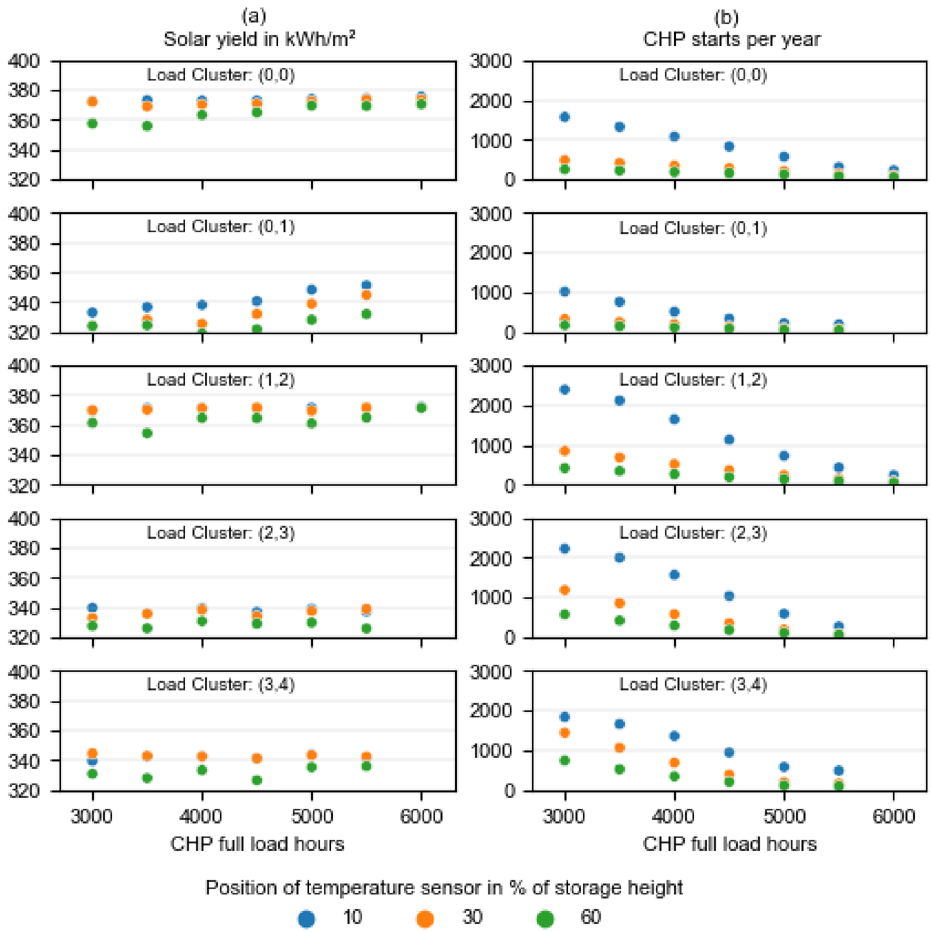

Fig. 4: TRNSYS simulation results: specific solar yield and CHP starts per year as a function of the CHP capacity for the different clusters and different heights of the CHP control node, annual heat demand 1 GWh/a

6. Conclusion and Outlook

The combination of solar heating plant and CHP is analyzed under various boundary conditions with TRNSYS simulations to evaluate how to combine both technologies most efficiently. The comparison of a one- and two-storage system shows that the technical performance of the one-storage system is beneficial. But as the system performance does not differ that significantly, both hydraulics can be realized efficiently, but are going to have different applications. If a CHP is already existing, the two-storage system can be the best option, as a smaller CHP storage is already existing, and the solar thermal system can simply be installed in parallel. If a new system is going to be implemented, the one-storage system should be installed as it is easier to control and only one storage is needed which reduces the investment. Furthermore, it is shown that the CHP operation can benefit of a large solar storage by reducing the starts and stops throughout the year which reduces the maintenance costs and extends the lifetime. The analysis of the CHP control highlights that the CHP should not be allowed to heat up the entire solar storage as this reduces the solar yield significantly from a certain point. These results can also be transferred to the combination of solar heating plants with other technologies such as biomass or heat pumps which must and can be operated more flexible compared to solar heating plants.

7. Acknowledgments

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