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Retrofitting of Industrial Utility Systems Considering Solar Thermal and Periodic Heat Storage

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Abstract This paper involves the development of a model that is based on mathematical programming for integrating solar thermal and heat storage with multi-period heat exchanger network (HEN) of industrial operations. The method employed entails discretising the availability of solar thermal on the basis of hourly, daily and monthly time periods using real-life climatic data for hourly solar irradiation and ambient temperature variations. Considering variability in the supply profile, a flowsheet superstructure of closed circuits including direct and indirect solar thermal utilization with periodic heat storage is first developed. Thereafter, the flowsheet is systematically connected with the modified stage-wise superstructure model formulation which allows utility selection at each stage of the HEN. The problem is formulated and solved in GAMS using Slovenia climatic data as a case study, while the objective function maximizes the solar heat output to the heat network. In average 25.9 % (139.6 kW) of hot utilities is saved due to solar thermal. The hourly profile of various climatic features considered within the model will enable more realistic solar heat forecasting for utility retrofit in existing designs and also for new designs.

Keywords: • Solar thermal • Periodic heat storage • Heat integration • Utility retrofit • Mathematical programming • Emission reduction •

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1 Introduction

Industries and chemical plants are increasingly confronted with the need to urgently respond to the threat of climate change and emission reduction, energy security as well as the continuous exposure to volatile energy costs. While the problems associated with energy security and high cost of energy could to a large extent be addressed through various energy efficiency measures (Worrell et al., 2009), the permanent solution to the carbon emission and climate change problems requires increased usage of various renewable energy sources in industrial utility systems (Klemeš et al., 2010). Among the various renewable energy resources, solar is indisputably a leading type of energy that is fast becoming relevant as a low-carbon source of heat and electricity. Solar is versatile, and it appears naturally at some elevated temperature without any mechanical work or energy input. This has the potential to offset considerable amount of energy costs and carbon emissions if properly integrated with industrial heat network. However, obtainable data in reality is in contrast to the global potential of solar energy as it still remained largely underutilized especially in industrial process heat application (World Energy Council, 2016). This may be due to variability of solar energy supply and technical difficulties in planning and decision making-process for practical applications (Chan et al., 2013). Hence, the inclusion of renewable energy in process heat demand and energy systems requires a systematic approach in order to circumvent the aforementioned supply variations.

In this study the production of heat from solar thermal is optimized on hourly basis according to measured meteorological data obtained from EC-JRC PVGIS (2017). An integrated design of a close circuit, direct and indirect solar thermal system with periodic heat storage is presented for utility retrofit of industrial heat exchange network system (HEN) considering the intermittent changes in supply of solar thermal, as well as the multiperiod changes in the profile of heat supply of the plant.

2 Methodology

The framework for solar heat network design for process utility retrofit (Figure 1) is organized to reflect the flow of harvested solar thermal through the major units and equipment for both direct and indirect utilization in the process plant.

The figure consists of a closed loop flowsheet superstructure of solar thermal incorporated with periodic heat storage, and systematic connection of the flowsheet with the stage-wise superstructure formulation of HEN (Yee & Grossmann, 1990), modified for multi-period operation and utility selection at each stage (Bogataj & Kravanja, 2012), to form a single integrated generic system. The resulting superstructure then comprises of three closed loops (i.e. solar panel – thermal storage – solar panel, solar panel – HEN – solar panel, thermal storage – HEN – thermal storage). The solar panel is connected to a splitter which makes it possible to use the heat captured either directly or channelled to heat storage tank for use at other hours of the day when there is no solar irradiation. Both the direct and indirect solar heat (DSH and ISH) are used to offset as much heat demand as possible that could be satisfied within the plant while it is assumed that high pressure steam (HPS) is also available as backup utility.

The harvested solar thermal is linked with HEN of the process plant via a mixer which makes room for switching between the direct and indirect solar heat connections. A second splitter is placed between the solar thermal-heat storage loop and the HEN to ensure efficient energy use in the integrated system such that the heat transfer fluid can return to the solar panel via the storage tank depending on whether the temperature level of return could be useful to buffer the heat storage fluid in the tank. An integration of solar thermal with the industrial HEN as shown in Figure 1 is implemented using the General Algebraic Modelling Systems (GAMS).

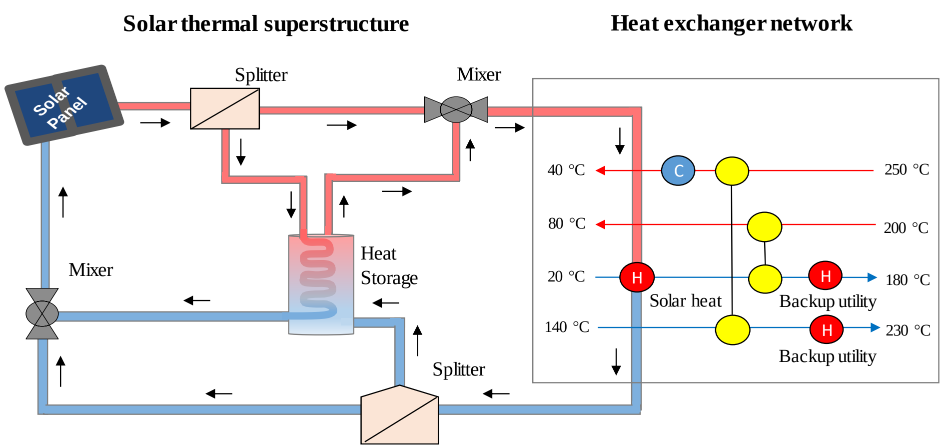

Figure 1: Integration of solar thermal with industrial heat exchanger network

3 Case Study

The model is implemented using Slovenia as case study. The coordinates of the area considered at this location are Latitude 46.552 N, Longitude 15.676 E and the elevation of 267 m. All the metereological data used were obtained from European Commission Joint Research Centre, PVGIS project (EC JRC PVGIS, 2017).

To test the efficacy and practical application of the model, an example of a process with two hot and two cold process streams (Smith, 2005) is adopted and modified for the special case of the solar heat retrofit of HEN presented in this study. The stream data for the modified example is presented in Table 1 and for simplification it is assumed to be fixed over the year.

Table 1: Hot and cold stream data for the modified example

	Supply Temperature °C	**Target Temperature** °C	**Heat Capacity Flowrate** kW/K	**Heat Flow** kW
H1	160	40	2.0	240
H2	180	70	2.0	220
C1	20	170	3.5	525
C2	40	150	4.3	473

ΔT_{min} = 10°C

Source: stream data modified from Smith, (2005)

To account for target design, in the first stage an expanded transshipment model (Papoulias and Grossmann, 1983) with minimal energy consumption as an objective is used. Based on the results obtained, process-to-process heat matches were fixed as: $Q_{\mathrm{H1\text{-}C1}}$ = 20 kW, $Q_{\mathrm{H1\text{-}C2}}$ = 220 kW and $Q_{\mathrm{H2\text{-}C1}}$ = 220 kW, and the cold utility consumption is set to 0. Hot utility consumption in the process is 538 kW.

To reduce computational time, model reduction techniques are applied using the procedure similar to that of Egieya et al. (2018), which is based on an earlier method presented by Lam et al. (2011). Instead of 24 hours a day, 8 periods are used, and instead of 28-31 days a month, 1 period is used. The model is based on mixed-integer non-linear programming (MINLP) with the objective of maximizing the average solar thermal use in the process plant in kWh in a year.

The final model consists of 36,005 single equations, 29,248 single variables and 60 binary variables and was solved using DICOPT solver in GAMS 25.1.1 modeling system (GAMS Development Corp. and GAMS Software GmbH, 2018). Solutions to the model were obtained within 725 s and 2,223,206 iterations by using personal computer with 64 GB of RAM and Intel® Core™ i7-8700 K CPU @ 3.70 GHz 3.70 GHz processor.

Table 2 shows the solar thermal use in HEN for each time-period where the quantities of heat exchanged are shown in kW(h/h). The last column shows the total amount of solar heat used in a specific month where the heat used in a process plant is summed for all time periods in a month (Q1-Q8), and is multiplied by 3 and number of days in a month.

Table 2: Results for solar thermal use in industrial HEN

Periods / Month	**3-6 am**	**6-9 am**	**9-12 am**	**0-3 pm**	**3-6 pm**	
	Q2 kW	**Q3 kW**	**Q4 kW**	**Q5 kW**	**Q6 kW**	**SUM kWh/month**
January	/	/	302.8	302.8	/	56,320.8
February	/	302.8	302.8	/	295.2	75,667.2
March	302.8	302.8	302.8	302.8	231.8	134,199.0
April	144.5	302.8	302.8	302.8	134.9	106,902.0
May	225.2	302.8	302.8	302.8	159.7	120,276.9
June	253.4	302.8	302.8	302.8	211.5	123,597.0
July	278.0	302.8	302.8	302.8	302.8	138,495.6
August	168.6	302.8	302.8	302.8	157.9	114,845.7
September	244.8	302.8	302.8	302.8	80.7	111,051.0
October	225.1	302.8	302.8	302.8	/	105,415.5
November	302.8	302.8	297.1	/	/	81,243.0
December	/	/	302.8	302.8	/	56,320.8
					SUM ($Q_{\text{Solar Exchanged}}$) in kWh/y	**1,224,334.5**

Based on the results, the month with the highest use of solar heat in the industrial HEN is July with a total of 138.5 MWh of heat exchanged. This is approximately 2.5 times higher than the months with the lowest potential for solar which are January and December with each of the months having 56.3 MWh of solar heat exchanged. A total of 1,224.3 MWh of heat is maximally exchanged from solar in a year. The maximum average heat power used in HEN from solar in a year (i.e. the objective value) is 139.62 kW (25.9 % of hot utility requirement in the plant). The optimal area of the panel selected is 3,000 m^2, the volume of fluid in the storage tank is 200 L, and the average amount of heat stored in a storage tank is 17.2 kW. Both area of the panel and volume of the fluid in the tank are selected at their upper and lower bounds. Due to the nonlinearity of the model, the closed loop constraint which is considered on the direct solar utilization (solar panel – HEN – solar panel) was also relaxed in order to obtain feasible solution for the model.

4 Conclusions

A new simultaneous approach for capturing solar thermal, considering the hourly changes in its availability, and the multiperiod profile of process heat supply in HEN has been presented in this paper. The method which is based on MINLP approach is capable of estimating the hourly, monthly and yearly availability of renewable energy for heat generation. Essential features that guarantee efficiency such as heat storage are included in the framework of the model. However, it should be noted that heat losses during heat transport and storage have not been considered. Nonetheless, the results obtained suggest that the model could be used as a decision support tool in the planning, design and operations of renewable energy systems. It should be noted also that the model is highly nonlinear and thus the obtained solutions are only locally optimal.

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