

# Design of Integrated Solar Thermal Energy System for Multi-Period Process Heat Demand

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This paper presents a new methodology for integrating renewable energy sources such as solar with chemical process utility demand. In chemical plant operations, the demand for utilities, as well as available process heat loads, are sometimes seasonal or multi-period in nature. Also, the availability of renewable energy such as solar, is time of day dependent as well as seasonal, i.e. time of year dependent. Therefore, in order to fully harness the economic and environmental benefits associated with the use of solar thermal energy, an approach which systematically integrates solar thermal radiation with process heat demand and other sources of utilities in chemical plants, while considering the multi-period profile of both the utility sources and the process streams need to be developed. The approach adopted in this paper, entails the use of the multi-period version of the stage-wise superstructure with an objective function involving a simultaneous minimisation of the annualised investment costs and annual operating cost of the network. The utility sources considered include solar and fossil fuel. The fossil fuel is included as a back-up depending on how much of the process heat demand is satisfied by solar energy. For the solar energy source, concentrated solar thermal collector is considered for both direct and indirect Heat Integration including thermal energy storage. In the example considered, a reasonable amount of cost savings was obtained when compared to the case without solar thermal integration.

## 1. Introduction

This paper presents a new methodology for integrating renewable energy sources such as solar with chemical process utility demand. An integration of this nature is imperative due to the ever rising cost of fossil based fuels and the attendant greenhouse gas emissions profile. Solar energy has been known to be environment friendly; however, other issues such as investment cost of solar panels and thermal storage vessels as compared to the cost associated with the use of conventional fossil based fuels in process plant operations has to be fully investigated so as to be able to evaluate the options. Since availability of solar thermal energy is variable in nature, i.e. time of day dependent as well as seasonal, it becomes imperative that a systematic approach needs to be developed so as to harness as much energy as possible from solar thermal radiation, in a cost efficient manner. For periods when solar thermal radiation is available, thermal storage tanks can be used to store thermal energy harvested from solar thermal collectors, for use at other times when solar thermal radiation is not available. This implies that a thermal storage tank having the right size (Nemet, et al., 2015) and kind of storage fluid has to be designed. Such tanks should not be too big such that they become very expensive and occupy large areas. Also, the storage tanks should not be too small such that they store too little heat or their heat dissipate too quickly. Further issues that has to be considered while integrating solar thermal energy with the energy pool of process plants, is the fact that, demand for energy by process streams is usually multi-period in nature. This multi-period profile may be as a result of environmental conditions, plant start-ups/shut downs, changes in product quality demand, etc. This implies that process stream parameters such as supply/target temperatures and flowrates may change from time to time due to any of the aforementioned factors. The heat exchanger network (HEN) design should be such that the heat duties of all process streams in all periods of operations are fully satisfied in a cost efficient manner. A study of this nature is necessary because most studies that involve integrating solar thermal energy with chemical plant process heat demand have mostly focused on non-continuous processes using heuristic based approach or pinch technology. The study of Nemet et al. (2015)

involves targeting the optimal solar collector area and size of thermal storage tank using sequential approach, while that of Atkins et al. (2010), which was based on pinch technology, did not consider thermal storage. A feature that is common to these two studies is that process heat recovery was first carried out before integration with solar thermal energy. However, since the method presented in this paper uses a simultaneous mathematical programming approach, and is based on continuous processes, all heat sources are integrated in a simultaneous manner. Other studies that integrated solar thermal energy with process heat demand using sequential approach include the work of Sharan and Bandyopadhyay (2015), where solar thermal energy was integrated with multiple effect evaporators, and that of Walmsley et al. (2014) where the benefits inherent in integrating low temperature solar thermal energy with heat recovery loop, considering parallel or series arrangement, using existing loop storage in heat recovery loop, were established.

The problem of harnessing energy efficiently from solar thermal radiation is further compounded by virtue of the fact that the availability of solar thermal energy, even though it is time of day and season of year dependent based on the geographical location, is not usually consistent within these periods. This is due to variations in the amount of solar irradiation reaching the geographical location concerned (Atkins, et al., 2010). Other factors that determine the amount of energy that can be harvested from solar thermal radiation include the size of the solar thermal collector as well as its efficiency, ambient temperature, average temperature of the capture fluid and its mass flowrate. Solar thermal heat can be captured during times when solar radiation is available and used at other times. The quality of such storage is dependent on the thermal capacity of the storage fluid as well as its inlet and outlet temperatures to the storage tank. Other factors that affect thermal energy storage include size of storage tank and rate of heat loss from the storage tank. Furthermore, in terms of heat demand by process streams, demand temperature may be higher than the maximum temperature of the solar panel capture fluid and storage fluid, which implies that not all of the heat demand by the process streams may be satisfied by solar thermal energy. As mentioned previously, the multi-period nature of the process heat demand further complicates the synthesis procedure, because, process parameters such as supply/target temperatures and heat capacity flowrates of process streams change from time to time based on issues such as varying environmental conditions, plant start-ups/shut-downs, change in product quality and/or demand, etc. In order to harvest thermal energy from solar irradiation in a cost efficient manner, so as to satisfy process heat demand in a multi-period scenario, a systematic approach has to be used. Also, a series of simplifying assumptions has to be made.

## 2. Problem statement

The problem statement addressed in this paper can be presented as follows: Given a set of hot and cold process streams whose supply and target temperatures, as well as heat capacity flowrates, vary according to a pre-defined manner, i.e. multi-period in nature. Given also are a set of hot and cold utilities, where the hot utilities comprise energy from renewable (solar) and non-renewable (fossil) sources, and the renewable energy is only available at specific times for specific durations in a day and year. Other parameters given are the global horizontal irradiation (GHI) and ambient temperatures ( $T_a$ ) for the plant location, solar panel optical efficiency ( $\eta_o$ ) and its thermal coefficients ( $a_1, a_2$ ), solar capture fluid and storage fluid properties, associated costs for the utilities and cost of solar panel, thermal storage tank and heat exchangers. It is desired to synthesize an optimal multi-period heat exchanger network that minimizes investment and utility costs.

## 3. Model approach

The example presented in this paper is for a scenario which has four seasons in a year and it is assumed that each of the seasons coincide with each of the periods of operations of the multi-period network. The multi-period network has four periods of operations. This implies that in season 1, the multi-period process operates at season 1 (also termed period 1 for consistency with identification in conventional multi-period models) with a specified set of process parameters. In season 2, the process operates at season 2 (i.e. period 2) with another set of specified process parameters that are unique to period 2. The same scenario applies to seasons 3 and 4, which also have their distinct set of process parameters. The four seasons/periods may not have equal durations; however, their combined duration comprises the operational year of the process plant. For each day in the operational year, three time intervals (also called periods in this study) are considered. The first and last time intervals of each day are the shady periods when solar thermal radiation is not available (i.e. late afternoons and night times), while the middle time interval is the period when solar thermal radiation is available (mostly early morning to mid-afternoon times). It should be known that since in reality, the daily number of hours having solar thermal radiation, as well as ambient temperatures, vary from day to day and from one season to another, average seasonal values have been used in the model developed in this study.

### 3.1 Model equations

As mentioned previously, due to the complexities involved in synthesizing integrated solar thermal energy and multi-period process heat demand, a mathematical programming approach, which is the multi-period version of the stage-wise superstructure (SWS) model of Yee and Grossmann (1990) is used in this paper. Due to space limitation, the detailed multi-period SWS model used will not be presented. The reader can find the details in the papers of Verheyen and Zhang (2006) for multi-period models involving single utilities, and Isafiade, et al. (2015) for multi-period models involving multiple utilities. The objective function presented by Isafiade and Fraser (2010) for multi-period problems, which adequately captures the weighting of the contribution of each utility to the network's annual operating cost, is also used in this paper. This is important since the utilities in the network, which are multi-period and multi-season in terms of availability, will not have equal contributions to the annual operating cost of the network due to variation in heat demand as well as the variabilities associated with availability of solar thermal radiation. It should be known that the model equations used in this paper is extended beyond that of Isafiade, et al. (2015) in that additional index 's' which represents each of the seasons of the operational year is included as also done by Isafiade and Short (2016). The key model equations that illustrate the integration of solar thermal collectors and thermal storage with multi-period processes while considering the daily and seasonal variation in availability of solar thermal energy are presented in Equations 1 to 4.

$$A_{i,j,k} \geq \frac{q_{i,j,k,s,p}}{(LMTD_{i,j,k,s,p}) (U_{i,j})} \quad (1)$$

$$\begin{aligned} \min \left\{ \sum_{s \in S} \sum_{p \in P} \left\{ \left[ \left( \frac{DOS_s}{\sum_{s=1}^{NOS} DOS_s} \right) \left( \frac{DOP_{s,p}}{\sum_{p=1}^{NOP} DOP_{s,p}} \right) \left( \sum_{i \in HP} \sum_{j \in CU} \sum_{k \in K} CUC_j \cdot q_{i,j,k,s,p} \right) \right] \right. \right. \\ \left. \left. + \left[ \left( \frac{DOS_s}{\sum_{s=1}^{NOS} DOS_s} \right) \left( \frac{DOP_{s,p}}{\sum_{p=1}^{NOP} DOP_{s,p}} \right) \left( \sum_{i \in HU} \sum_{j \in CP} \sum_{k \in K} HUC_i \cdot q_{i,j,k,s,p} \right) \right] \right\} \right\} \\ + AF \left[ \sum_{i \in HP} \sum_{j \in CP} \sum_{k \in K} CF_{ij} \cdot y_{i,j,k} + \sum_{i \in HP} \sum_{j \in CP} \sum_{k \in K} AC_{ij} \cdot A_{i,j,k}^{ACI} \right. \\ \left. + \sum_{i \in HP} \sum_{j \in CP} \sum_{k \in K} ACSC_{ij} \cdot ASC_{i,j,k} \right. \\ \left. + \sum_{i \in H} \sum_{j \in C} \sum_{k \in K} ACTS_{ij} \cdot VTS_{i,j,k} \right] \quad (2) \end{aligned}$$

$$ASC_{i,j,k} \geq \frac{q_{i,j,k,s,p}}{\eta_0(GHI_{s,p}) - a_1(T_c - Ta_{s,p}) - a_2(T_c - Ta_{s,p})^2} \quad (3)$$

$$VTS_{i,j,k} \geq \frac{q_{i,j,k,s,p}}{c_p \rho (T^s - T^t)} \quad \forall i \in HP, j \in CP, k \in K, s \in S, p \in P \quad (4)$$

Eq(1) represents the area of the representative heat exchanger for the same pair of streams exchanging heat in more than one period (i.e. daily time interval used to classify availability of solar radiation) and more than one season of operation. This exchanger is made to have the maximum of the areas required by the stream pair in the periods and seasons concerned. In Eq(1),  $A_{i,j,k}$  represents the area ( $m^2$ ) of the heat exchanger connecting hot stream  $i$  and cold stream  $j$  in stage  $k$  of the superstructure,  $LMTD_{i,j,k,s,p}$  represents the logarithmic mean temperature difference ( $^{\circ}C$ ) between hot stream  $i$  and cold stream  $j$  in stage  $k$  of the superstructure and in season  $s$  and period  $p$ ,  $q_{i,j,k,s,p}$  represents the heat (kW) exchanged between hot stream  $i$  and cold stream  $j$ , in season  $s$  and period  $p$ , while  $U_{i,j}$  represents overall heat transfer coefficient between hot stream  $i$  and cold stream  $j$  ( $0.25 \text{ kW}/(m^2 \cdot ^{\circ}C)$ ). In Eq(2), which is the objective function,  $DOS_s$  represents the duration of season  $s$ ,  $NOS$  represents number of seasons,  $DOP_p$  represents duration of period  $p$ ,  $NOP$  represents the number of periods,  $CUC$  represents cost of cold utility ( $13 \text{ } \$/(\text{kW} \cdot \text{y})$ ),  $HUC$  represents cost of hot utility ( $290 \text{ } \$/(\text{kW} \cdot \text{y})$ ),  $AF$  is the annualisation factor ( $0.149$ ),  $CF_{ij}$  represents heat exchanger installation cost ( $8,333.3 \text{ } \$$ ),  $y_{i,j,k}$  is the binary variable which indicates the existence, or otherwise, of a match between the hot and cold streams,  $AC_{ij}$  represents area cost of heat exchangers ( $641.7 \text{ } \$/m^2$ ) while  $ACI$  represents heat exchanger area cost index ( $0.83$ ).  $ACSC_{ij}$  is the area cost ( $100 \text{ } \$/m^2$ ) for solar panel, while  $ASC_{i,j,k}$  is the area ( $m^2$ ) of the solar panel that feeds the heat unit that exchanges heat between the capture fluid (hot utility  $i$ ) and cold process stream  $j$  in

interval  $k$  of the superstructure.  $ACTS_{ij}$  is the cost (50 \$/m<sup>3</sup>) of thermal storage tank while  $VTS_{i,j,k}$  is the volume (m<sup>3</sup>) of thermal storage tank that feeds the heat exchanger that exchanges heat between the storage tank fluid (hot utility  $i$ ) and cold process stream  $j$  in interval  $k$  of the superstructure.  $T_c$  (°C) is the average of the inlet and outlet temperatures of the solar capture fluid.  $GHI_{s,p}$  is the global horizontal irradiation for the location of the plant in season  $s$  and period  $p$  while  $Ta_{s,p}$  is the ambient temperature in season  $s$  and period  $p$  as well.  $a_1$  and  $a_2$  which are experimental constants (1.53 W/(m<sup>2</sup>·K) and 0.0003 W/(m<sup>2</sup>·K)), are called the thermal loss coefficients.  $\eta_0$  is the solar panel efficiency factor (76.4 %),  $c_p$  is the heat capacity (4.2 kJ/(kg·°C)) of the storage fluid while  $\rho$  is its density (1,000 kg/m<sup>3</sup>).  $T^s$  and  $T^t$  (°C) are the supply and target temperatures of hot utility  $i$ , used as the storage fluid. Eqs.(3) and (4), just like the maximum area  $A_{i,j,k}$  in Eq.(1), are meant to ensure that the selected solar panel area size and thermal storage tank are big enough to capture the required amount of thermal energy to serve process heat demand in all seasons and periods of operations concerned, so they do not have indices  $s$  and  $p$ .

#### 4. Example

The example used to demonstrate the new method for integrating solar thermal energy with the process heat demand of multi-period heat exchanger networks involves two hot process streams, five cold process streams, 3 hot utilities, and one cold utility. One of the hot utilities (represented as HU3 in Figure 1) is steam and is obtained from fossil fuel. This utility is available at a temperature of 300 °C. The other two utilities, which are both water, are part of the solar thermal network. One of these utilities (represented as HU1) is used as the solar capture fluid. This fluid, whose inlet and outlet temperatures to the solar panel are fixed at 60 °C and 120 °C, captures heat from the solar panel and then transfers it to the rest of the heat exchange network in two ways. The first transfer mechanism is the direct solar Heat Integration where the captured heat is exchanged with cold process streams in hot utility exchangers. In the second transfer mechanism, which is the indirect Heat Integration, the fluid (HU1) exchanges the heat captured from the solar collector with a thermal storage tank. These two heat transfers happen in period 2 of each day in every season, using solar panels whose areas represent the maximum that may be required in period 2 of any day and any season of the operational year. The reason for the use of Eq(3) for determining the solar collector area. This equation ensures that the collector area is not under-designed for days/seasons with low solar radiation and ambient temperatures. The heat stored in the thermal storage tank is transferred from the tank by the second utility in the solar thermal network to the cold process streams passing through utility exchangers. This fluid (represented as HU2 in Figure 1) has its inlet and outlet temperatures to the storage tank fixed at 50 °C and 110 °C. This implies that a 10 °C minimum approach temperature is allowed for feasible heat exchange. In the example considered, there exists four seasons that comprise an operational year and each season is assumed to last for three months (see Table 1). Period durations in terms of length of availability of solar radiation for each day (in hours) are also shown in Table 1. Note that it has been assumed that the 2 periods in each season without solar radiation (i.e. periods 1 and 3) have equal durations as shown in Table 1. It should be known that direct Heat Integration serves period 2, while indirect Heat Integration serves periods 1 and 3. However, the heat stored in the thermal storage tanks are captured in period 2. Storing this heat for periods 3 and 1 will incur some heat losses, especially for period 1, therefore in order to accommodate these losses, thermal storage tanks for period 3 are assumed to be 15 % larger than the normal size while those of period 1 are made 30 % larger than their normal size. The average GHI for each season of an operational year is used to determine the areas of the solar collectors. Table 1 also shows the average ambient temperatures for each of the four seasons. Stream data for all the four seasons and periods are shown in Table 2.

Table 1: Period and season durations and other data used in this paper

Seasons (durations in months)	Periods (durations in h)			Ambient temperature for period 2 $T_a$ (°C)	GHI (kW/m <sup>2</sup> ) Period 2
	1	2	3		
1(3)	7.2	9.6	7.2	32	0.8
2(3)	8.6	6.8	8.6	22	0.6
3(3)	9.9	4.2	9.9	18	0.4
4(3)	8.4	7.2	8.4	22	0.6

A multi-period and multi-season stage-wise superstructure having five stages was applied to this example and a solution with a total annual cost of 4,294,000 \$ was obtained in 16.7 min of CPU time. The integrated network is shown in Figure 1. This network has 20 heat exchangers, 12 solar thermal collectors and 8 thermal storage tanks. Of the 20 heat exchangers, 13 are hot utility exchangers while the rest are process heat exchangers. Out

of the 13 utility exchangers, 8 exchangers (i.e. exchangers 6, 8, 9, 11, 12, 15, 17, 20 as labelled in Figure 1) are served by HU1 and HU2. As mentioned previously, these two utilities are heated by the 12 solar thermal collectors. Utility exchangers connected to HU1 (i.e. exchangers 6, 8, 9, 15) are involved in direct solar Heat Integration, hence they operate in period 2 of each day and in all seasons of the operational year where solar radiation is available. These exchangers are served by solar collectors SC5, SC6, SC7 and SC8 as shown in Figure 1. The area for each of these collectors is shown in Table 3. It should be known that the heat load on these exchangers would vary due to the seasonal variation in GHI and ambient temperatures as shown in Table 1. Utility exchangers connected to HU2 (i.e. exchangers 11, 12, 17, 20), which are served by the thermal storage tanks (ST1, ST3, ST2, ST4 in period 1, and ST9, ST11, ST10, ST12 in period 3), are involved in indirect solar Heat Integration, hence they operate in periods 1 and 3 of each day and each season.

Table 2: Multi-season and multi-period stream data

Stream	Seasons (durations in months)	Heat capacity flowrate F (kW/°C)	T <sub>IN</sub> (°C)	T <sub>OUT</sub> (°C)
HP1	1 (3)	10.2	110	58
	2 (3)	11.0	100	56
	3 (3)	12.0	102	54
	4 (3)	11.5	108	50
HP2	1 (3)	6.00	150	48
	2 (3)	5.00	155	45
	3 (3)	5.50	162	42
	4 (3)	6.50	158	40
CP1	1 (3)	21.5	15	172
	2 (3)	20.0	18	175
	3 (3)	22.0	22	185
	4 (3)	22.5	20	190
CP2	1 (3)	22.2	33	122
	2 (3)	22.0	31	120
	3 (3)	23.0	30	128
	4 (3)	23.2	28	130
CP3	1 (3)	18.0	22	172
	2 (3)	17.6	25	170
	3 (3)	17.5	27	170
	4 (3)	17.2	30	170
CP4	1 (3)	22.6	25	270
	2 (3)	22.7	23	280
	3 (3)	22.7	29	265
	4 (3)	22.7	26	268
CP5	1 (3)	22.5	75	260
	2 (3)	22.6	73	270
	3 (3)	22.6	79	275
	4 (3)	22.6	76	288

Table 3: Solar collector and storage tank sizes

Solar collector	Area (m <sup>2</sup> )	Thermal storage tank	Volume (m <sup>3</sup> )
Indirect Heat Integration (season s, period 1)			
SC1	3,898	ST1	266
SC2	3,299	ST2	225
SC3	3,070	ST3	210
SC4	4,612	ST4	315
Direct Heat Integration (season s, period 2)			
SC5	4,467		
SC6	3,717		
SC7	3,524		
SC8	5,240		
Indirect Heat Integration (season s, period 3)			
SC9	3,898	ST9	301
SC10	3,299	ST10	255
SC11	3,070	ST11	237
SC12	4,612	ST12	356

in period 1 are SC1, SC2, SC3, SC4 with areas shown in Table 3, while the solar collectors for period 3 are SC9, SC10, SC11, SC12, with areas also shown in Table 3. The areas of solar collectors in periods 1 and 3 are the same because they both capture heat in the same period (i.e. period 2) and the heat demand by process streams is not period dependent. However, their thermal storage tank volumes are different due to differences in assumed heat losses. It should be known that if the problem had been solved without the option of integration with solar thermal energy, a solution with a total annual cost of 4,947,000 \$/y would be obtained. This cost is about 13 % higher than the cost obtained for the integrated case.

## 5. Conclusions

A new synthesis approach for integrating solar thermal energy with continuous multi-period heat exchanger networks has been presented in this paper. The new method takes into consideration, the variability of solar radiation, ambient temperature as well as the variability of process heat demand in a heat exchanger network. Other methods in the literature, which only considered single period operations, used sequential approach for the integration of solar thermal energy in chemical plant process heat demand. Hence these methods do not involve simultaneous trade-offs among the competing variables in a complex system of this nature. Further studies that include detailed sensitivity analysis needs to be carried out so as to establish the effect of changes in parameters such as solar collector area cost, thermal storage tank cost, solar collector inlet and outlet temperatures, utility costs and temperature range, annualisation factors, geographical locations, etc., on the total annual cost of the network. Furthermore, energy from other renewable sources such as biomass, wind,

and even photovoltaic, should be explored so as to establish a more holistic view of the economics and environmental benefits associated with the use of renewable energy sources.

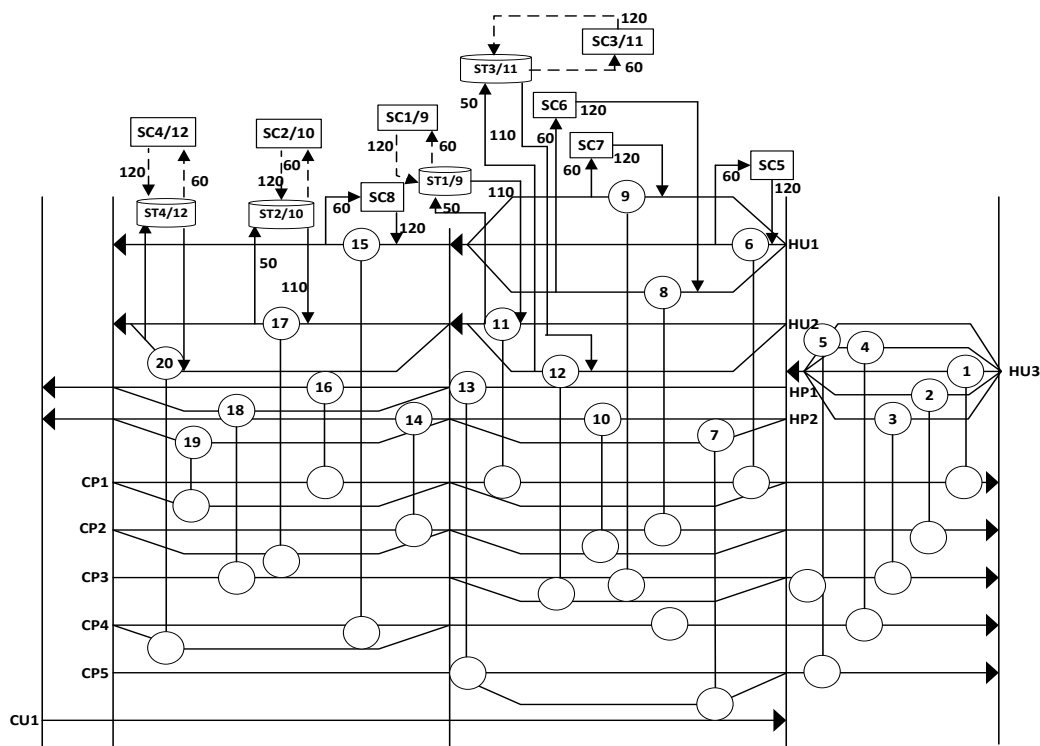


Figure 1: Heat exchanger network showing integrated solar thermal collectors and thermal storage tanks

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