CHEMICAL ENGINEERING TRANSACTIONS
VOL. 39, 2014
A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet
Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Peng Yen Liew, Jun Yow Yong

**ISBN** 978-88-95608-30-3; **ISSN** 2283-9216
DOI: 10.3303/CET1439061

# Options for Solar Thermal and Heat Recovery Loop Hybrid System Design

Michael R. W. Walmsley*, Timothy G. Walmsley, Martin J. Atkins, James R. Neale

University of Waikato, Energy Research Centre, School of Engineering, Hamilton, New Zealand
m.walmsley@waikato.ac.nz

Integration of solar thermal energy into low temperature pinch processes, like dairy and food and beverage processes is more economic when combined with a Heat Recovery Loop (HRL) to form a hybrid inter-plant heat recovery system. The hybrid system shares common infrastructure and improves solar heat utilisation through direct solar boosting of the HRL intermediate fluid’s temperature and enthalpy either through parallel or series application. The challenge of dealing with variable solar energy supply is less of a problem in the hybrid system because the HRL with its associated storage acts as an enthalpy buffer which absorbs temperature and flow rate fluctuations on both the heat supply (including solar) and heat demand side simultaneously. Three options for integrating solar thermal directly into HRLs are applied to a large multi-plant dairy case study to demonstrate the hot utility savings potential of the Solar-HRL hybrid system. HRL performance with Variable Temperature Storage (VTS) and solar is dynamically modelled with historical plant data. The series configuration is shown to be consistently better than parallel configuration for the same thermal storage volumes and similar heat exchanger areas.

## 1. Introduction

Using solar to generate steam and hot water for process heating is of growing interest to industry and governments. As a step forward to global energy sustainability, using solar energy for process heating has tremendous potential and makes a lot of sense, especially for industries that require large amounts of low-temperature water in the 40 to 80 °C temperature range (i.e. low pinch temperature) that are located in countries with high levels of sunshine. These types of industries are numerous e.g. food, dairy, meat, beverage, textile, agricultural and chemical industries.

Identifying the best solar integration point in a process and the best solar integration concept from a technical and economic point of view is a significant challenge, especially while fossil fuels remain a cheap source of heat (Kiraly et al., 2013). One opportunity that lowers the cost of solar process heat is to integrate solar with an indirect heat recovery system like a Heat Recovery Loop (HRL) (Walmsley et al., 2014). With a HRL, heat recovery is achieved with the aid of an intermediate fluid, usually water, that circulates through a heat exchanger network from cold to hot storage and then from hot to cold storage in a continuous loop (Figure 1a). The storage acts as a buffer to mass and enthalpy imbalances between the hot and cold sides of the loop and is ideal for improving heat recovery on large multi-process sites with lots of semi-continuous processes in operation. This approach enables the solar installation to share common infrastructure with the HRL, because the same issues around variable heat supply and variable heat demand have to be dealt with in both systems.

In previous works, the benefits of applying solar process heating using a HRL were demonstrated in both a variable temperature storage (VTS) approach and the conventional constant temperature storage (CTS) approach (Walmsley et al., 2014). Methods were developed for maximising the uptake of variable solar heat supply in a low pinch temperature semi-continuous process (Atkins et al., 2010a) and for Total Site Analysis (Nemet et al., 2012). General aspects of HRL design, thermal storage (Walmsley et al., 2009), seasonal operation effects (Atkins et al., 2010b) and heat exchanger area optimisation (Walmsley et al.,

Please cite this article as: Walmsley M.R.W., Walmsley T.G., Atkins M.J., Neale J.R., 2014, Options for solar thermal and heat recovery loop hybrid system design, Chemical Engineering Transactions, 39, 361-366 DOI:10.3303/CET1439061

2013) have also been reported. Related studies helpful on solar thermal systems utilizing pressurized hot water storage (Kulkarni et al., 2008), types of solar collectors and thermal energy storage systems (Tian and Zhao, 2013), and system performance optimisation and economic analysis (Kim et al., 2012). Several industrial case studies have also been presented at the 2013 IEA SHC Technology Workshop on Solar Process Heat for Industry for a dairy factory and the brewing industry (RHC, 2014).

In this paper using a dairy industry case study from New Zealand (Walmsley et al., 2014), the benefits of integrating low temperature solar thermal into a HRL in either parallel or series configuration using existing loop storage in the HRL are examined.

## 2. Integrating Solar Collectors into a HRL

Options for integrating solar collectors into a HRL loop are presented in Figure 1. The variable supply of solar throughout a day/night cycle is integrated within the HRL system without the need for additional storage (Options B, C, D) unless a third tank is used (Option E & F). The overlap region of the Compisote Curves (CC) represents the time-average HR target. As solar is added loop exchangers are resized to ensure heat transfer on both sides of the loop remain in long term balance. Variable Temperature Storage (VTS) is considered. Results for Constant Temperature Storage (CTS) have been previously shown to be similar to VTS (Walmsley et al., 2013).

***Option A*** is the standard two tank HRL without a solar collector. A pinch fixes the temperature of the cold storage temperature (for the case shown), whereas the hot storage temperature can be varied in small range. The slope of the line between these two points represents the inverse of the loop flow rate, and the overlap region is the maximum average HR.

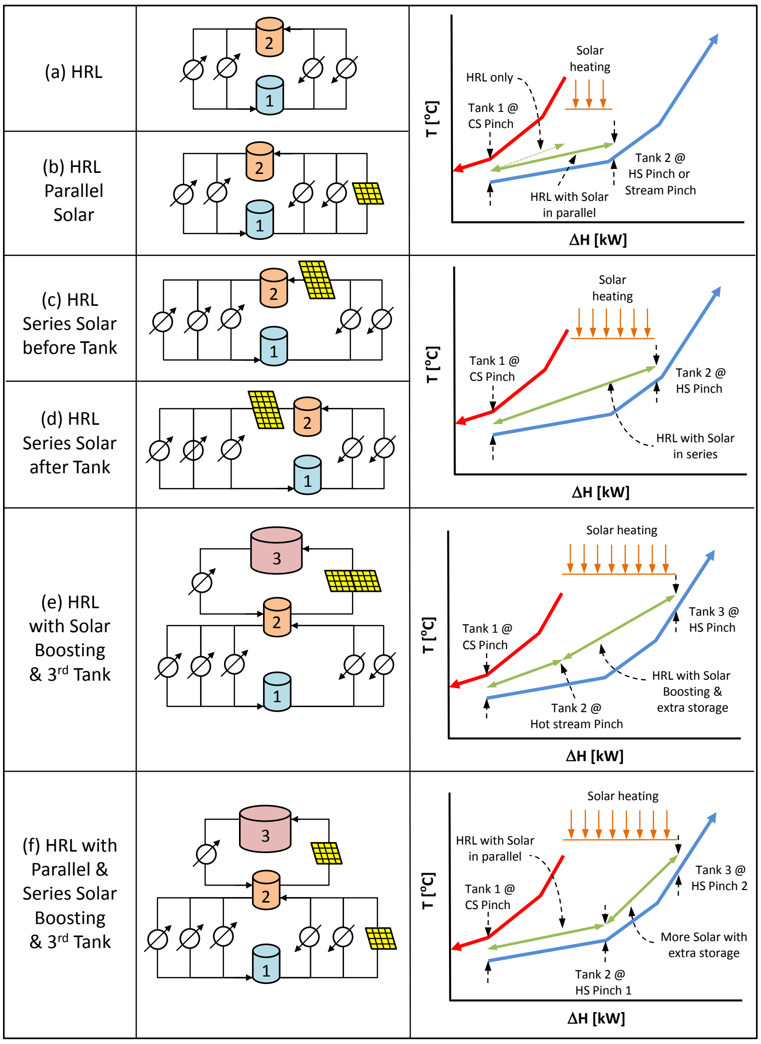


*Figure 1: Solar-HRL hybrid system configurations and Composite Curves*

***Option B*** uses a solar collector in parallel with the HRL heat sources and the hot loop fluid is mixed when returning to the hot storage using the VTS control method. Extra flow through the solar collector increases the flow rate of the loop, as illustrated by the lower slope of the loop line, and extends the heat transfer possibilities to a new hot pinch point which is a combination of HR from hot streams (same as option A) and additional solar which varies from day to night.

***Option C*** uses the solar collector in series as a temperature booster of the hot loop fluid before storage. The loop flow rate is not affected by the solar collector, and hence the loop line on the CC extends at the same slope until it reaches a hot storage pinch. Depending on the shape of the cold CC a higher solar level may be possible compared to the parallel solar-HRL system (option B).

***Option D*** is similar to option C except the solar collector is now after the hot storage and fluctuations in solar radiance are not dampened by storage. The CC remains the same as does the predicted maximum HR and Solar use.

***Option E*** is similar to option A except a third tank and a second solar boosted loop has been added which gets around the hot pinch of tank two and the conventional HRL. The third tank could be larger than tank 1 and 2 to provide extra capacity to smooth differences between day/night solar collection.

***Option F*** is similar to option B except a third tank and second solar boosted loop has been added which gets around the hot pinch of tank two and of the parallel solar-HRL system. The temperature of Tank two will rise and fall from day-to-night and the upper loop will interact with these fluctuations as it too fluctuates with varying solar radiance. Feasible solar heat recovery will possibly be much lower as a result of these interactions. The optimal tank storage volume to minimise dynamic effects and maximise HR is needed.

## 3. Industrial Case Study

Adding Solar Thermal Collectors to an existing HRL a large multi-plant dairy factory is investigated. The factory consists of eight separate semi-continuous plants that share common utility, power and materials handling services. Plants initially were integrated to industry best practice. Sometime later liquid streams still requiring substantial heating or cooling duties were fitted to a HRL. Further reductions in utility use are being sought through gaseous dryer exhaust heat recovery and solar thermal heating to the HRL.

### 3.1 Steady State HRL Design and Transient Heat Recovery Modelling Methods

This study applies the steady state $\Delta T_{min}$ HRL design method presented by Walmsley et al. (2013), and expanded in Walmsley et al. (2014) for Variable Temperature Storage (VTS) with solar thermal. Thermal storage temperatures ($T_c$, $T_h$), streams to include on the HRL and heat exchanger areas are sized based on time-average heat capacity flow rates (C) to give a balanced loop. The HRL model of Walmsley et al. (2013) for transient stream data analysis is also applied to calculate the heat recovery for a defined time period. For the VTS method, the outlet temperature of the intermediate loop fluid ($T_{L,SP}$), which is the set point, was set to be a $\Delta T_{min}$ (5 °C) from the process stream's supply temperature. Solar collector efficiency and duty has been modelled using the design equations and constants given by Atkins et al. (2010a). Typical solar radiation and ambient temperatures are taken from a New Zealand weather station. The effect of changing the tank storage capacity is not considered. Results are based on using existing tanks of 500 $m^3$ each. The intermediate fluid is water. Solar-HRL configuration options B, C, and D are considered in the study.

### 3.2 Data Extraction

Inter-plant process stream data was obtained from the factory for a period of two months during peak processing at intervals of 10 minutes. Heat capacity flow rate (C) and stream duty (Q) were reported as average plant 'operating' values with no interruption and 'time-averaged' values across the entire two months of peak production. The process streams considered are given in Table 1, and the CCs based on 'time-averaged' heat capacity flow values for streams without dryer exhaust HR are presented in Figure 2a and with dryer exhaust streams in Figure 2b and Figure 3.

### 3.3 Utility and Heat Recovery Targeting

Figure 2 compares the minimum hot and cold utility consumption and maximum HR for solar-HRL hybrid system in parallel configuration (option B) with dryer exhaust HR (Figure 2a) and without dryer exhaust HR (Figure 2b). Adding dryer exhaust enables HRL performance to increase from 6.3 MW to 11.3 MW, while reducing solar effectiveness from 3.1 MW average to 1.0MW average. It is apparent from the CCs that dryer exhaust HR which produces intermediate fluid at 60 °C, limits the quantum of solar possible compared to the case without exhaust HR. Switching to a series configuration - Figure 3 (Option C&D), with dryer exhaust HR, debottlenecks the system and enables solar heating to increase to 2.3 MW average for a combined total of hot utility reduction of 13.6 MW. Note that for parallel solar configuration

*Table 1: Extracted stream data including the spray dryer exhaust and solar heating*

| Stream | Type | $T_t$ [°C] | $T_s$ [°C] | Operating C [kW/°C] | Operating Q [kW] | Time-average C [kW/°C] | Time-average Q [kW] |
|---|---|---|---|---|---|---|---|
| Dryer Exhaust A | HOT | 75 | 55 | 143 | 2,851 | 139 | 2,785 |
| Dryer Exhaust B | HOT | 75 | 55 | 75 | 1,497 | 73 | 1,462 |
| Dryer Exhaust C | HOT | 75 | 55 | 45 | 898 | 44 | 877 |
| Dryer Exhaust D | HOT | 75 | 55 | 29 | 570 | 28 | 557 |
| Utility Unit A | HOT | 45 | 30 | 10 | 146 | 8 | 120 |
| Utility Unit B | HOT | 45 | 30 | 10 | 146 | 8 | 120 |
| Casien A | HOT | 50 | 20 | 33 | 999 | 22 | 647 |
| Casien B | HOT | 50 | 20 | 49 | 1,477 | 32 | 956 |
| Casien C | HOT | 50 | 20 | 49 | 1,485 | 32 | 962 |
| Condenser | HOT | 80 | 79 | 993 | 993 | 351 | 351 |
| Cheese A | HOT | 35 | 20 | 120 | 1,797 | 98 | 1,470 |
| Cheese B | HOT | 35 | 20 | 139 | 2,074 | 114 | 1,691 |
| Solar Collector | HOT | 85 | - | - | - | - | - |
| Site Hot Water (SHW) | COLD | 16 | 65 | 160 | 7,827 | 160 | 7,827 |
| Milk Treatment A | COLD | 10 | 50 | 104 | 4,159 | 104 | 4,159 |
| Milk Treatment B | COLD | 10 | 50 | 104 | 4,159 | 104 | 4,159 |
| Milk Treatment C | COLD | 11 | 50 | 116 | 4,563 | 116 | 4,563 |
| Whey A | COLD | 12 | 45 | 20 | 663 | 16 | 522 |
| Whey B | COLD | 14 | 45 | 11 | 340 | 9 | 267 |

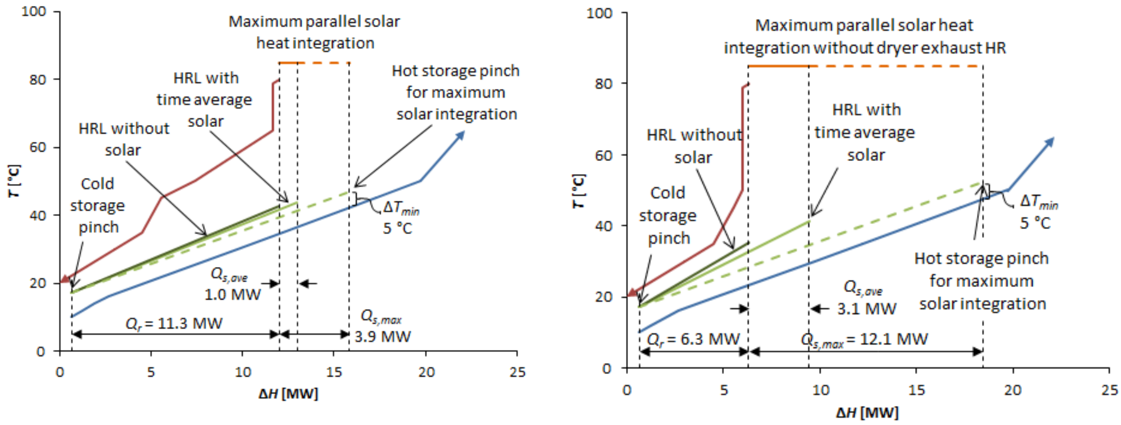


*Figure 2: Composite Curves for Solar-HRL hybrid system with parallel solar collectors, with exhaust heat recovery (a, left) and without exhaust heat recovery (b, right)*

the solar stream is heated to a maximum of 80 °C, whereas with the series heating solar can exceed 80 °C during the peak solar irradiance levels of a sunny day.

In series configuration HR levels are identical to the parallel case at 11.3 MW but the maximum solar heating levels are higher at 9.0 MW compared to 3.9 MW for parallel. When day/night fluctuations of solar are taken into account average levels of solar produced heat are around 2.3 MW, which is approximately 25 % of the maximum. This is similar to the parallel case when exhaust HR is excluded. Average solar contribution is 1.0 MW. With seasonal variation also taken into account this average solar energy value will fall even lower, which is one of the challenges of solar thermal systems. With more storage and larger solar collector area the average output of solar heating can be increased but not without on-going interaction between the CCs and the variable storage temperatures on the loop.

The solar heating contribution represented by the extended lines on the CCs (Figures 2a, 2b and 3), beyond the HRL intermediate fluid line, represent the solar heating potential only. With direct solar heating into the HRL, as proposed in this investigation, the HR to the sink side of the loop is variable depending on the time of day and level of solar radiance present for collection. Heating due to solar therefore moves up and down between the HRL end point with no solar to the hot storage pinch point with solar. If solar heat is available at enthalpy levels that exceed the hot storage pinch, for example in the middle of the day on a

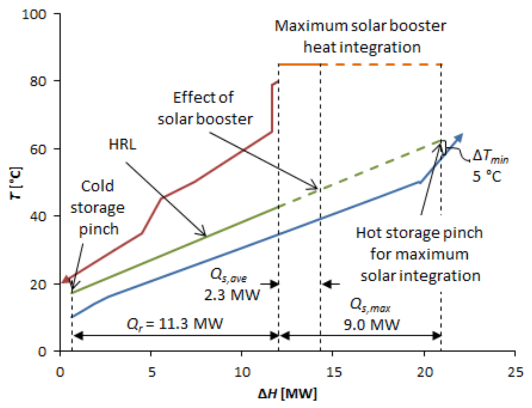


Figure 3: Composite curves for Solar-HRL hybrid system with series solar collectors.

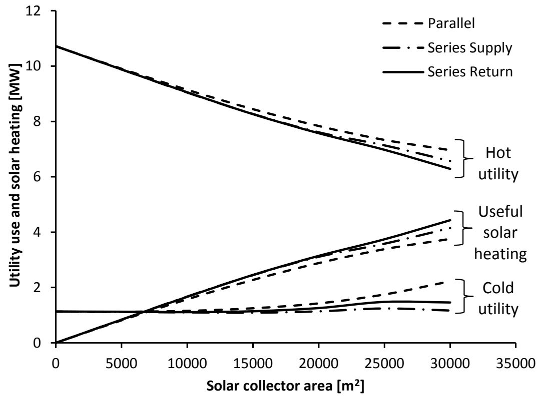


Figure 4: Solar-HRL hybrid system performance with constant hot and cold storage of 500 m$^3$.

very hot day, the hot storage tank will quickly fill and before long extra cold utility is required to maintain a balanced loop. To avoid the need for more cooling utility the solar system needs to be designed to produce a maximum enthalpy output that reaches the hot pinch only. Over the course of a 24 hour cycle the average heat contribution from the solar will be approximately 25 % of this maximum value (Walmsley et al., 2014). This issue can be overcome if indirect solar heating of the HRL intermediate fluid was used, with all the added expense of an independent solar loop with storage. Twenty-four hour delivery of solar produced hot water to the HRL would then be possible. One would still need additional backup utility to cover for poor days of sunlight, and therefore such a solution will be expensive.

### 3.4 Transient Modelling of Solar-HRL Hybrid Systems

The results of transient modelling of the three cases using real and variable plant data are presented in Figure 4 for hot and cold storage volumes of 500 m$^3$. With increasing solar collector area hot utility decreases for each case with series return configuration (option C) showing the greatest reduction followed by series supply (option D) and then the parallel configuration (option B). Similarly the useful solar heating levels were greatest for the series configurations (options C&D) and lower for the parallel case (option B) as predicted by the CC's. The cold utility results are quite interesting. Initially there is no difference between the configurations but after about 11,000 m$^3$ cold utility begins to rise above the value of 1.1 MW, first for the parallel configuration and then eventually for the other cases. The increase in cold utility arises as a consequence of the hot storage pinch that arises first in the parallel configuration. The presence of more collector area drives solar heating to increase the loop heat capacity flow rate to a level that is out of balance with the heat sinks on the cold side of the HRL and the hot storage tank fills to where more cold utility is now required. For series configurations this arises at a later point as predicted by the CC's. With increasing solar collector area the series return case (option C) has a lower cold utility use compared to the series supply case (option D). This may arise due to the difference in hot temperature variability to the sink heat exchangers for the two cases.
Increasing solar collector area to 30,000 m$^3$ causes the parallel configuration to asymptote to a maximum average useful solar of 3.9 MW as predicted by the CC (Fig. 2a). For series configuration the maximum average solar is not reached but continues to rise to an asymptote at 9.0 MW, again as predicted by the CC. The increased cooling utility observed combined with the useful solar is the total solar collected. With increased solar area beyond 22,000 m$^2$, not all of the solar is able to be usefully used all the time and the increased solar is achieved with extra cooling arising, which may be counterproductive. The extra cooling utility is a complex relationship between solar collector area, stream variability of the source and sink streams, variability of the solar and the volume of storage. It has only been able to be predicted using the transient HRL spreadsheet model developed for the case study.
An example of storage tank levels and hot and cold storage temperatures derived from the transient HRL model are presented in Figure 5. The solar boosting effect arising from the solar can be clearly seen for both configurations. The parallel configuration has smaller temperature fluctuations compared to the series configuration, and the flow-on effects to the cold tank temperature arise during the extreme temperature peaks observed in the series configuration. For the series configuration hot tank temperatures fluctuate from a low of around 39 °C at night to a peak of up to 80 °C in the middle of the day. Parallel configuration, on the other hand fluctuates with a lower range between 39 °C and 60 °C.

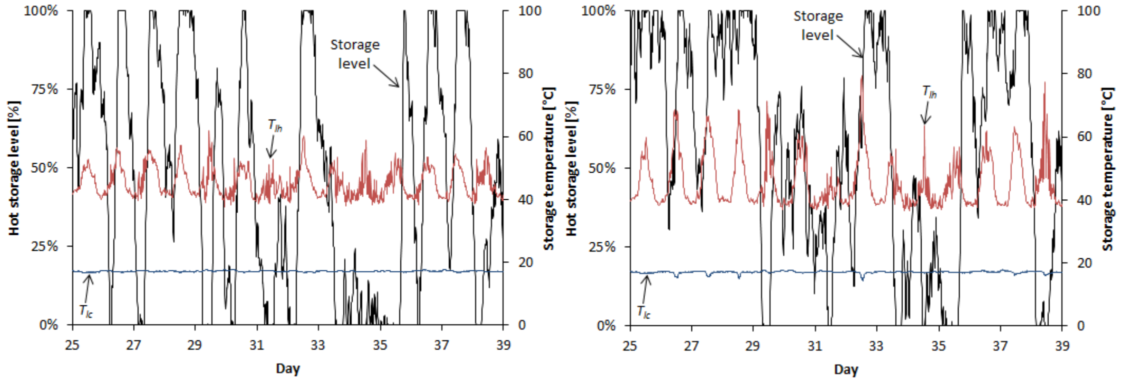


*Figure 5: Hot storage tank levels and hot and cold storage tank temperatures for the Solar-HRL hybrid system with parallel solar (a, left) and return series solar (b, right), with 15,000 $m^2$ solar collector area and 500$m^3$ tank volume*

When peak storage temperatures are present, for example in the series configuration case, it is interesting to observe that the cold tank temperature drops into a trough during the peak load period and then returns to normal again. This is caused by the reduction in flow rate on the sink side of the HRL loop to compensate for the higher hot tank temperature which in turn causes a lower exit temperature to maintain a fairly constant LMTD driving force in the loop exchanger. Likewise hot tank levels are seen to rise when peak temperatures are present also in response to the reduction in flow to the sink side of the loop. This effect is more pronounced in the tank level data observed for a solar collector area of 30,000 $m^2$.

## 4. Conclusions

Integration of solar thermal into a HRL with VTS control is desirable way of achieving significant cost effective hot utility savings without the need for extra infrastructure like storage. A series configuration for the solar collectors in the HRL is superior to a parallel configuration. The performance of the Solar-HRL hybrid system can be targeted by Pinch Analysis using time average heat capacity flow rate values. Prediction of actual performance is more difficult and requires development of a transient model that accounts for the variability of process streams on the HRL and variable solar supply.

## References


Atkins M.J., Walmsley M.R.W., Morrison A.S., 2010a. Integration of solar thermal for improved energy efficiency in low-temperature-pinch industrial processes. Energy, 35, 1867–1873.

Atkins M.J., Walmsley M.R.W., Neale J.R., 2010b. The challenge of integrating non-continuous processes – milk powder plant case study. Journal of Cleaner Production, 18, 927–934.

Kim Y.-D., Thu K., Bhatia H.K., Bhatia C.S., Ng K.C., 2012, Thermal analysis and performance optimization of a solar hot water plant with economic evaluation, Solar Energy, 86, 1378-1395.

Kiraly A., Pahor B., Kravanja Z., 2013, Achieving Energy Self-Sufficiency by Integrating Renewables into Companies' Supply Networks. Energy, 55, 46-57.

Kulkarni G.N., Kedare S.B., Bandyopadhyay S., 2008, Design of solar thermal systems utilizing pressurized hot water storage for industrial applications, Solar Energy, 82, 686-699.

Nemet A., Klemeš J.J., Varbanov P.S., Kravanja Z., 2012. Methodology for maximising the use of renewables with variable availability. Energy, 44, 29–37.

RHC European Technology Platform <www.rhc-platform.org> accessed 25.07.2014

Tian Y., Zhao, C.Y., 2013, A review of solar collectors and thermal energy storage in solar thermal applications, Applied Energy, 104, 538-553.

Walmsley M.R.W., Atkins M.J., Riley J., 2009. Thermocline management of stratified tanks for heat storage. Chemical Engineering Transactions, 18, 231–236.

Walmsley M.R.W., Walmsley T.G., Atkins M.J., Neale J.R., 2013, Methods for improving heat exchanger area distribution and storage temperature selection in heat recovery loops, Energy, 55, 15-22.

Walmsley M.R.W., Walmsley T.G., Atkins M. J., Neale J. R., 2014, Integration of industrial solar and gaseous waste heat into heat recovery loops using constant and variable temperature storage, Energy, In Press, DOI: 10.1016/j.energy.2014.01.103.