

Integration of Solar Heating into Heat Recovery Loops using Constant and Variable Temperature Storage

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
walmsley@waikato.ac.nz

Solar is a renewable energy that can be used to provide process heat to industrial sites. Solar is extremely variable and to use it reliably thermal storage is necessary. Heat recovery loops (HRL) are an indirect method for transferring heat from one process to another using an intermediate fluid (e.g. water, oil). With HRL's thermal storage is also necessary to effectively meet the stop/start time dependent nature of the multiple source and sink streams. Combining solar heating with HRL's makes sense as a means of reducing costs by sharing common storage infrastructure and pipe transport systems and by lowering non-renewable hot utility demand. To maximise the value of solar in a HRL, the means of controlling the HRL needs to be considered. In this paper, the HRL example and design method of Walmsley et al. (2013) is employed to demonstrate the potential benefits of applying solar heating using the HRL variable temperature storage (VTS) approach and the conventional HRL constant temperature storage (CTS) approach. Results show the VTS approach is superior to the CTS approach for both the non-solar and solar integration cases. When the pinch is around the hot storage temperature the CST approach is constrained and the addition of solar heating to the HRL decreases hot utility at the expenses of increased cold utility. For the VTS approach the hot storage pinch shifts to a cold storage pinch and increased heat recovery is possible for the same exchanger area without solar. With solar the VTS approach can maintain the same heat recovery while also reducing hot utility still further due to the presence of solar, but only with additional area. When the pinch is located around the cold storage temperature, solar heating can be treated as an additional heat source and the benefits of CTS and VTS are comparable.

1. Introduction

Integration of renewable heat sources into chemical processes is increasingly becoming an area of intense research. Solar thermal stands out as viable candidate for providing heating to low pinch temperature processes. However solar heating is often uneconomic due to the large amount of infrastructure needed to ensure constant day and night heat supply. Where multiple low temperature semi-continuous processes are clustered on a single site, inter-plant heat integration may be effectively achieved using a Heat Recovery Loop (HRL) as illustrated in Figure 1. Heat storage, as a part of the HRL system, is needed to successfully meet the time dependent nature of the source and sink. Seeing that HRL's already have most of the infrastructure needed for solar heating there exists a nexus between the two concepts that may be utilised for their mutual advantage. Typically hot and cold storage temperatures in HRL's are fixed and the source and sink streams heat and cool the intermediate fluid between two storage temperature levels.

Several recent studies by the authors have considered various parts of the design, operation and optimisation of HRL's including: thermal storage management options such as a stratified tank (Walmsley et al., 2009); changes to storage temperature for seasonal production changes (Atkins et al., 2010b); utilisation and sizing of thermal storage capacity (Atkins et al., 2012); characterisation of historical stream flow rates for HE area sizing (Walmsley et al., 2012); and, the evaluation of different HE sizing methods through simulation of HRL performance for transient stream data (Walmsley et al., 2013). Recently, Chen and Ciou (2009) optimised an indirect heat recovery system for a batch process by allowing the target temperature set points of the intermediate fluid to differ for each HE resulting in a variable temperature

storage system, which change offered improved heat recovery. In other areas, methods have been developed for maximising the integration of solar heating for low pinch temperature processes (Atkins et al., 2010a) and Total Site Analysis (Nemet et al., 2012). However the economics of solar heating systems are often poor due to the infrastructure required to not only collect radiation heat, but also to store the heated fluid overnight. The integration of solar heating into a HRL is mutually beneficial because the HRL system provides the heat storage while solar is an additional heat source (Figure 1).

Conventional control of a HRL is to measure and compare the outlet temperature of the loop fluid from each heat exchanger (HE) to a common hot or cold temperature set point. To achieve the set point, the flow rate of the loop fluid through the HE is adjusted. An important characteristic of this approach is hot and cold storage temperatures are constant over time. An alternate approach to HRL control is to vary the set points of the HE's depending on their temperature driving force. This alternate approach is characterised by variable temperature storage (VTS) tanks due to mixing of different temperatures entering the tanks.

This paper aims to look at the effects of CTS versus VTS operation of a HRL system with and without including solar as an additional heat source. The VTS approach has not been widely applied to HRLs, even though the possibility exists for improvements in indirect heat recovery from a simple operational change and the reallocation of some area. With this approach, the intermediate fluid flow rate is controlled to give an outlet temperature that is ΔT from the supply temperature of selected source or sink streams on the loop. Over time the storage tank temperature and volume both vary depending on the thermal loads on the loop and the variability of the streams, which is modelled using the same spreadsheet tool applied by Walmsley et al. (2013). Solar heating may be added to a HRL to increase the quantity and upgrade the quality of heat storage depending on the location of the pinch temperature and the shape of the process Composite Curves.

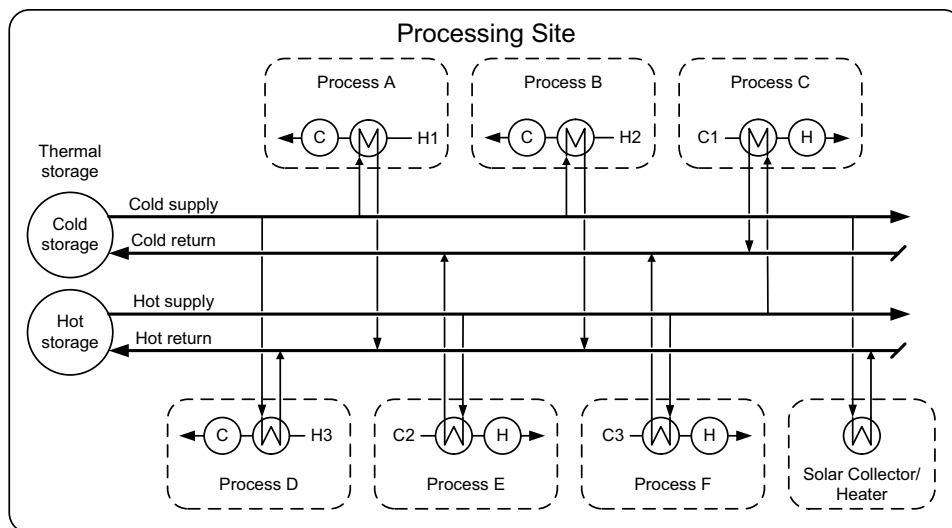


Figure 1: Heat recovery loop network with integration of solar heating

2. Heat recovery loop network design and modelling methodologies

This study applies the steady state ΔT_{\min} HRL design method presented by Walmsley et al. (2013), which method is also discussed in detail in the book by Klemeš et al. (2013). Using this method, thermal storage temperatures (T_c , T_h) and streams to include on the HRL are determined and HE areas are sized based on time-average heat capacity flow rates (CP). The HRL model of Walmsley et al. (2013) for transient stream data analysis is also applied to calculate the heat recovery.

Four methodologies for operating and designing a HRL, including the integration of solar heating, have been considered.

HRL design and operation methods:

1. Conventional design method ($\Delta T_{\min} = 5 \text{ }^\circ\text{C}$) with constant temperature storage (CTS) control.
2. Variable Temperature Storage (VTS) HRL design and operation method. For this method, HE's are sized and controlled to enable the outlet temperature of the intermediate loop fluid ($T_{L,SP}$), which is the set point, to be a ΔT_{\min} ($6.9 \text{ }^\circ\text{C}$) from the process stream's supply temperature. The ΔT_{\min} is purposely chosen so that the total area is the same as method 1.

3. Integration of solar heating into the CTS HRL design from method 1 using $\Delta T_{\min} = 5^\circ\text{C}$.
4. Integration of solar heating into the VTS HRL design from method 2 using $\Delta T_{\min} = 6.9^\circ\text{C}$

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 hot and cold tanks of 150 m^3 each. The intermediate fluid considered is water.

3. Heat recovery loop example problem

3.1 HRL stream data and utility demand

Inter-plant process stream data is given in Table 1. The data is taken from Walmsley et al. (2013) where the full transient characteristics are presented. In Figure 2 the time averaged Composite Curves ($\Delta T_{\min} = 5^\circ\text{C}$) of the available streams to be attached to the HRL are presented. Heat recovery and hot and cold utility demand values are shown as steady-state targets. A hot pinch arises due to the supply temperature of stream H2.

Table 1: Inter-plant process stream data

Stream	T_s [$^\circ\text{C}$]	T_t [$^\circ\text{C}$]	CP_{ave} [$\text{kW}/^\circ\text{C}$]	Q [kW]
H1	43	6	7.1	263
H2	70	10	3.5	210
H3	56	18	4.6	175
C1	10	40	5.1	153
C2	12	75	2.3	145
C3	16	55	11.8	460

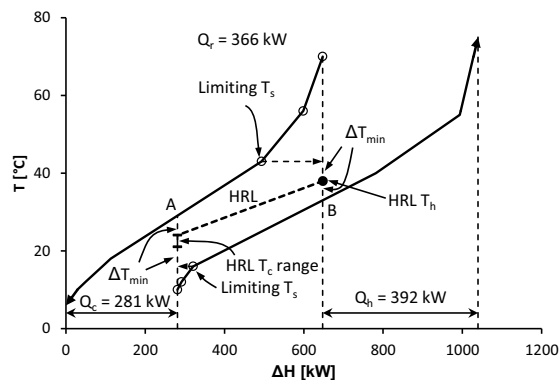


Figure 2: HRL targeting using a ΔT_{\min} approach with CTS, and time average Composite Curves; $\Delta T_{\min} = 5^\circ\text{C}$, $T_h = 38^\circ\text{C}$ and $T_c = 21 - 24^\circ\text{C}$.

4. Results and discussion

4.1 Constant versus variable temperature storage operation of HRL's

Table 2 compares the HE areas, loop temperature outlet set points ($T_{L,SP}$), hot/cold utility consumptions and heat recovery for methods 1 and 2. The total area for the methods is the same (92.4 m^2). The difference between methods 1 and 2 is a change in control set points and a reallocation of area using the VTS design method. These changes resulted in decreasing hot and cold utility use by 16 kW, which is 4.4 % extra heat recovery.

Table 2: Comparison of HE areas, intermediate loop outlet temperature set points, $T_{L,SP}$, hot/cold utility consumption and heat recovery using methods 1 and 2. *Average value for the 100 h period.

Stream	Method 1 (CTS)			Method 2 (VTS)		
	Area [m^2]	$T_{L,SP}$ [$^\circ\text{C}$]	$Q_{\text{h or c}}^*$ [kW]	Area [m^2]	$T_{L,SP}$ [$^\circ\text{C}$]	$Q_{\text{h or c}}^*$ [kW]
H1	18.8	38.0	165	14.0	34.3	157
H2	9.5	38.0	69	16.2	58.2	65
H3	11.7	38.0	53	15.4	45.8	47
C1	13.7	23.5	37	15.2	16.7	32
C2	6.2	23.5	101	6.2	19.0	99
C3	32.5	23.5	260	25.3	23.4	249
Totals	92.4			92.4		
		Q_h	397		Q_h	381
		Q_{solar}	0		Q_{solar}	0
		Q_c	286		Q_c	269
		Q_r	361		Q_r	377

Figure 3 shows the HRL performance in terms of the amount of available hot storage, and the instantaneous hot and cold tank temperatures for methods 1 and 2, which lead to two important results. First, the models show that method 2 maintains on average a hotter hot storage temperature (43.3 °C compared to 38.0 °C for method 1), which leads to the slight increase in heat recovery. Second, the difference between hot and cold storage temperatures is greatest for method 2 (22.2 °C compared to 14.5 °C for method 1). This 53 % increase in temperature difference effectively increases the specific thermal storage capacity by the same percentage. This is seen in Figure 3 where the minimum hot storage level is 10 % (15 m³) for method 1 compared to 25 % (37 m³) for method 3. However, the advantages of using a VTS approach are no doubt dependent on the process. In general, the VTS approach is most successful when there is a stream's supply temperature causing a pinch around one of the storage temperature levels effectively constraining the maximum possible heat recovery (Figure 2).

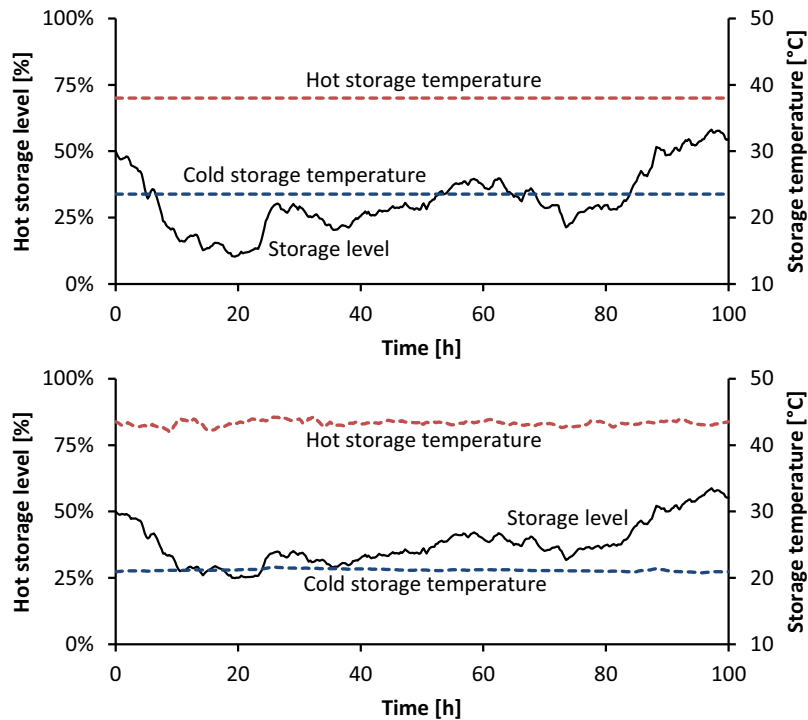


Figure 3: HRL performance for a 100 h period for method 1 (a) and 3 (b) excluding solar heating.

4.2 Integration of solar heating with HRL's

The integration of solar heating with HRL's is logical because both systems need thermal storage to account for their variable heat supply/demand throughout a day/cycle. Figure 4 illustrates the effect of integrating solar heating into two general cases, which may be characterised by the location of the pinch.

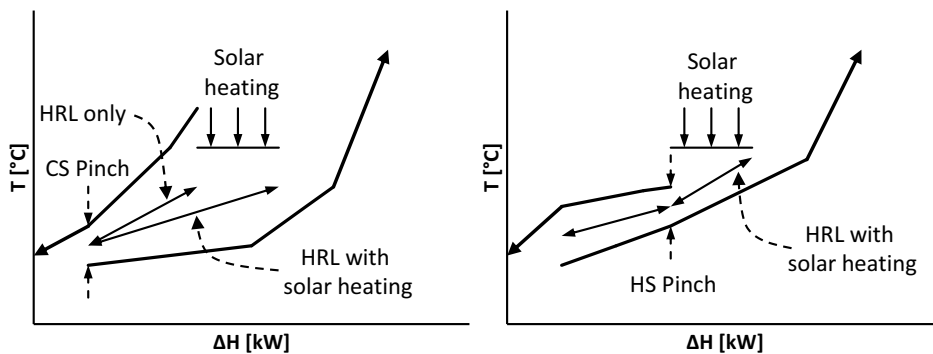


Figure 4: Composite Curves for the integration of solar heating with HRL's for processes with limited quantity, i.e. enthalpy, of sources (a) and limiting quality of sources, i.e. temperature (b).

In the first case (Figure 4a) the pinch is at the cold storage temperature indicating a significant lack of heat sources. As a result solar heating may be simply integrated as an additional heat source and either CTS or VTS control may be applied to operate the HRL. It may be economic to further increase the area of the cold side exchangers to ensure that the extra heat from solar is optimally used by the HRL.

The second case (Figure 4b) is where the pinch is located around the hot storage temperature. The hot storage pinch may be caused by the start of the hot Composite Curve (Figure 4b) or a limiting supply temperature as in the example (Figure 2). Applying solar heating to produce hot water at the pinched hot storage temperature is ineffective and inappropriate because the solar source becomes a pseudo-hot utility below the pinch (Atkins et al., 2010a). To generate benefits from adding solar the HRL fluid temperature needs to be raised above the pinch temperature and some modification to the HRL design and/or operation may need to be made. If a CTS operating approach is used, then a third storage tank and new heat exchanger(s) is needed to take advantage of the extra heat available (Figure 4b). With a third storage tank, the solar heat replaces expensive hot utility with no change to the cold utility requirement.

If a VTS operating approach is used, similar to method 2, it is feasible to run the HRL with two tanks by maintaining a mixed hot storage temperature above the pinch temperature based on the conventional CTS targeting approach. At a higher hot storage temperature a greater proportion of the process heating requirements may be achieved using recovered heat or solar heat. Additional heat exchanger area is needed to take full advantage of introducing solar as a heat source as a result for methods 3 and 4 their respective ΔT_{\min} values are kept constant while the total area slightly increases.

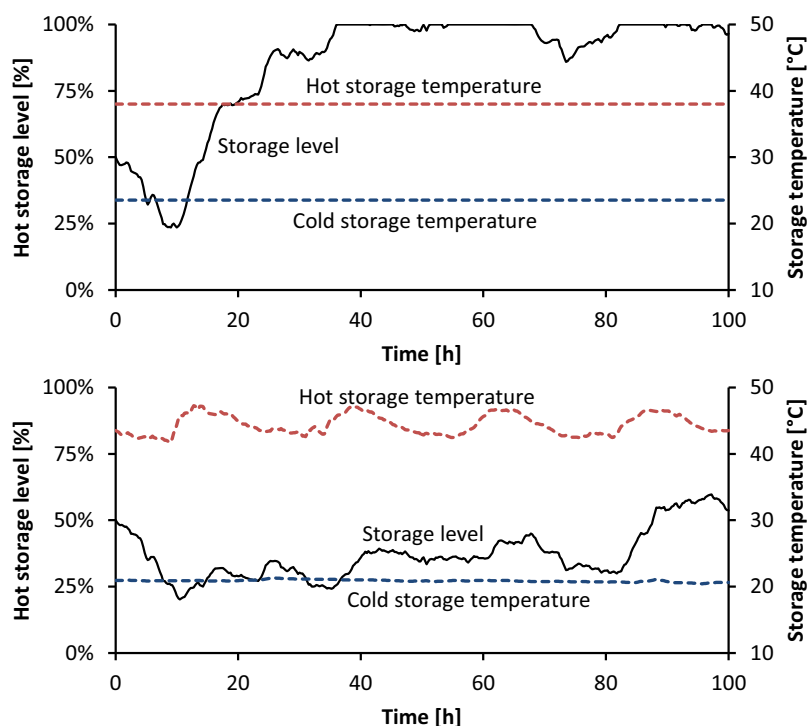


Figure 5: HRL performance including solar heating for a 100 h period for method 4. Solar collector area is 250 m², loop outlet temperature from collect is 70 °C.

Figure 5 shows the HRL performance for the integration of solar heating into CTS operation (method 3) and VTS operation (method 4) using the HRL design parameters presented in Table 3. For method 3 the addition of solar heating (57 kW) does not decrease hot utility, rather cold utility increases by 57 kW, which is needed to cool fluid from the hot tank down to the cold tank to maintain the running of the HRL. As a result of excess heating, Figure 5a shows the hot storage tank reaches its zenith with no sink in which to place the solar heat due to a lack of temperature.

Method 4 uses a VTS operation, which allows the integration of solar to increase the quantity and upgrade the mixed temperature of the hot storage tank. Figure 5b shows the hot storage temperature and fluid storage level oscillates significantly between day and night. With the additional area of 14.1 m², method 4 successfully reduces hot utility demand by 61 kW while cold utility is decreased by 4 kW due to a slightly lower on average cold storage temperature. The daily average heat collection from solar is 57 kW.

Future work aims to formulate a formal method for targeting the heat recovery potential of the VTS approach including a target for maximum solar heat integration. There also remain further questions about how best to integrate solar into a HRL.

Table 3: Comparison of HE areas, intermediate loop outlet temperature set points, $T_{L,SP}$, hot/cold utility consumption and heat recovery using methods 3 and 4. *Average value for the 100 h period.

Stream	Method 3 (CTS inc. Solar)			Method 4 (VTS inc. Solar)		
	Area [m ²]	$T_{L,SP}$ [°C]	$Q_{h\ or\ c}^*$ [kW]	Area [m ²]	$T_{L,SP}$ [°C]	$Q_{h\ or\ c}^*$ [kW]
H1	18.8	38.0	165	13.7	33.9	156
H2	9.5	38.0	69	15.4	57.0	64
H3	11.7	38.0	53	14.9	45.1	46
C1	13.7	23.5	37	19.5	16.8	16
C2	6.2	23.5	101	8.1	18.9	92
C3	32.5	23.5	260	34.9	22.9	212
Solar	250.0	70.0	57	250.0	70.0	-
		Q_h	397		Q_h	230
Totals	92.4 (+250.0)	Q_{solar}	57	106.5	Q_{solar}	223
		Q_c	343	(+250.0)	Q_c	343
		Q_r	361		Q_r	

5. Conclusions

Inter-plant indirect heat integration via a HRL combined with renewable solar heating is potentially an economic method for increasing process energy efficiency in large processing sites with a low pinch temperature. How solar heating is integrated depends on the pinch temperature and the shape of the CC's. Where HRL pinch temperatures are located around the cold storage temperature, solar heating can be directly integrated as an additional source without the need for an additional storage tank. Where HRL pinch temperatures are located around the hot storage temperature results show that both the constant and variable temperature storage approaches to operating a HRL are beneficial. However, the CTS approach requires a third tank whereas the VTS approach can bring benefits without the need for an extra tank. Changing the operation of an existing HRL without solar from constant temperature storage to variable temperature storage may also be advantageous, but it depends on the exact position of the stream supply temperatures. To realise the full benefits of changing to VTS operation or the addition of solar, a redistribution of the existing heat exchanger area is needed.

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.
- Atkins, M.J., Walmsley, M.R.W., Neale, J.R., 2012. Process integration between individual plants at a large dairy factory by the application of heat recovery loops and transient stream analysis. *Journal of Cleaner Production* 34, 21–28.
- Chen, C.L., Ciou, Y.J., 2009. Design of indirect heat recovery systems with variable-temperature storage for batch plants. *Ind. Eng. Chem. Res.* 48, 4375–4387.
- Klemeš, J.J. (Ed.), 2013. *Handbook of process integration: Minimisation of energy and water use, waste and emissions*. Woodhead Publishing, Cambridge, UK.
- 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.
- 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., 2012. Area Targeting and Storage Temperature Selection for Heat Recovery Loops. *Chemical Engineering Transactions* 29, 1219–1224.
- 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* 10.1016/j.energy.2013.02.050.