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Total Site Heat Integration with Seasonal Energy Availability

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Total Site Heat Integration (TSHI) approach has been extended to the Locally Integrated Energy Sectors (LIES) that include small scale industrial plants, renewable energy sources with variable supplies, and residential as well as commercial buildings as energy consumers with fluctuating demands. TS targeting methodology with Time Slices, which is comparable to Heat Integration for batch processes, have been introduced for a short-term, day-to-day analysis. Energy storage facility is integrated in the TS to address the problem of energy supply variation. However, previous studies have mostly dealt with the daily or short term variations. This work introduces an extended methodology for TS integration for the long-term energy supply and demand planning. The work is important in solving cases with a considerable temporal fluctuation of heat sources/sinks, in order to obtain more energy saving opportunities within a longer period of time (i.e., in the scale of weeks or even months). The energy fluctuation in processing plants may be caused by seasonal climate variations, long-term customer demands or even economic down-turn. Some other possibilities include operability issues and raw material availability. The methodology can also be implemented for district heating and cooling systems in countries with four seasons, assuming energy excess during the summer can be stored for use in other seasons e.g. during the winter. This methodology is demonstrated by a case study which involves integration of batch processing plants and space heating system together with cooling system which only operates during certain periods of time. Several scenarios which affect the long-term energy supply and demand have been assumed.

1. Introduction

Renewable energy source has a great potential in reducing the dependency on fossil fuels. Many studies have been done by researchers to find the alternative sources of energy for use in the industrial and urban sectors. The Pinch Analysis has an established tool for energy integration to reduce the energy usage as well as to increase the energy intensity in the industries.

The Pinch Analysis tool has been extended to consider energy integration across several plants or processes using indirect heat transfer (Dhole and Linnhoff, 1993), termed as Total Site (TS) heat integration. The methodology has been extended by Raissi (1994) and developed further by Klemeš et al. (1997). The major tools involved in the analysis include the Grand Composite Curves (GCCs), the Total Site Profiles (TSPs), the Site Composite Curves (SCC), and the Site Utility Grand Composite Curves (SUGCC). These tools have been developed to enable visualisation of the heat availability and consumptions on the TS. Numerical algorithms have been recently introduced for TS analysis (Liew et al., 2012). The numerical tool such as the Total Site Problem Table Algorithm (TS-PTA) has been extended from the graphical approaches mentioned.

The initial TS concept has only considered the energy conservation between industrial processes. Perry et al. (2008) have conceptually introduced the renewable energy as the heat source and have included the urban energy consumptions known as Locally Integrated Energy System (LIES), into the TS concept. Varbanov and Klemeš (2011) published a TS heat cascade, which has shown the relation between process, steam system, renewable energy and heat storage. However, the intermittent renewable energy

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sources (e.g. solar and wind) typically varies with time and location (Nemet et al., 2012). Similar to the methodology for individual batch processes heat integration, the Time Slices (TSLs) methodology is introduced to handle the variable nature of the renewable energy supply and urban energy demands (Varbanov and Klemeš, 2011). Wan Alwi et al. (2012) have recently introduced an algorithmic solution for tackling this variability issues.

However, the previous works have only considered the daily or the short term variation of energy sources and demands. There is a room for further development by utilising heat excess at a hot season (summer) for the cold season (winter) without considering the minor daily variations. A TS methodology has been extended in this work from the TS Heat Storage Cascade (TS-HSC) proposed by Wan Alwi et al. (2012) to simultaneously address both the long and the short term energy availability issues. The proposed methodology is essential for TS applications in the temperate countries that incorporate renewable energy sources and urban energy demands. The methodology is also applicable for processes that are prone to long term demand fluctuations and economic down turns.

2. Seasonal and Short Term Variations

Renewable energy supply as well as energy demands have the tendency to fluctuate at different times. Energy consumption by the urban and industrial sectors are definitely different for summer and winter seasons. Figure 1 shows a conceptual illustration of the relationship between seasonal and short term energy demand variations. The instability of the daily and seasonal energy demands and supplies are more visible when energy supplies from renewable and decentralised power plants are used to satisfy the energy demand (Kato, 2007). There are often surplus energy generated from certain seasons and more energy is needed at specific season. As a result, energy surplus at a given season could be considered for storage and utilised during seasons with energy deficits.

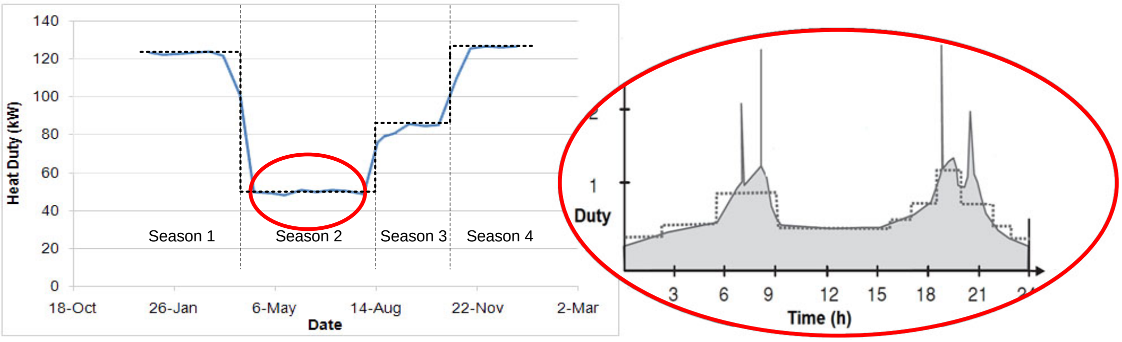

Figure 1: Seasonal and short term energy demand variations

There are several major types of thermal energy storage system available in the market, which are physical energy storage (latent heat, sensible heat) and chemical storage - heat of sorption and heat of reaction (Kato, 2007). Energy storage via heat of reaction is comparatively less spacious among the storage methods (Pinel et al., 2011). In energy losses, physical thermal storage gradually loses its energy by heat conduction and radiation. Chemical storage stored energy as reactants/ products with small losses (Kato, 2007). There are several chemical reactions which have been studied for seasonal or long-term storage, e.g. hydrogen storage (Bielmann et al., 2011), calcium chloride in ammonia - $CaCl_2/NH_3$ (Kato, 2007) and sodium hydroxide – NaOH (Weber and Dorer, 2008).

3. Methodology

The proposed methodology for targeting the minimum utility requirements of a TS system which considers seasonal energy availability variation is defined as below. It is beneficial where the proposed methodology has adapted to the two TS methodologies available – graphical and numerical.

STEP 1: Identify the seasons with the huge temporal variations of the energy availability.

STEP 2: Identify the TSLs for each season from the variations of process energy supplies, demands and renewables (Nemet et al., 2012).

STEP 3: Determine the utility requirement at each TSL for each season by using the graphical approach (Klemeš et al., 1997) and also the numerical approach (Liew et al., 2012). The TS Pinch location for each TSL can also be determined at this stage.

STEP 4: Determine the external utility needed/ surplus for each season via the TS methodology with TSLs (Varbanov and Klemeš, 2011)and the TS-HSC (Wan Alwi et al., 2012).

STEP 5: Determine the overall external utility needed/ surplus for the whole long term cycle using the newly proposed TS methodology with the Seasonal TS-HSC. The tool is designed for one type of utility in a table. The detailed construction is listed as below:

a) Input the seasons determined from STEP 1 in ascending order.
b) Determine the length of each season and record in Column 2 (Table 6)
c) Record the utility consumption of the specific type of utility during continuous operation for all seasons. The external hot utility requirement is recorded in negative value to indicate heat deficits, while external cold utility is recorded in positive value as heat excess.
d) Calculate the utility consumption for the whole long term cycle in Column 4 (Table 6).
e) A cascade of available enthalpy is performed for each season in Column 5 starting from the highest to the lowest TSL. The heat cascade is the summation of energy available brought from previous TSL and net MU available.
    a. For seasonal operation cycle start up, it is assumed that there is no heat being stored. The storage cascade starts from zero load. External Heating Utility (EHU) is added in Column 6 when the storage cascade shows a heat deficit (negative value) after every time interval. After EHU is added, the cascade should become a net zero enthalpy in the storage cascade instead of utility deficit. The amount of heat excess in the storage system by the end of the first seasonal cycle, e.g., a year, is termed as seasonal heat surplus (SHS).
    b. External Cooling Utility (ECU) is added to the heat storage cascade to eliminate the heat surplus from the system. This step avoids accumulation in the storage system and also reduces the storage capacity.
        i. If the Total EHU is less than the SHS (Total EHU <SHS) during the start-up operation, a negative quantity of ECU (Column 7 of Table 6) should be added into the storage cascade at the earliest positive energy available in the same cascade. The quantity of ECU added should be able to yield an equal amount of total EHU and the SHS (Total EHU = SHS). Another storage cascade is performed for the continuous operation of the TS, which only requires ECU for the TS system. Note that the amount of heat excess cooled down by ECU can also be let-down to the lower utility level when there is a requirement.
        ii. If the Total EHU is higher than the SHS (Total EHU >SHS) during the start-up, bring the SHS in operation start-up cycle to the next cycle of seasons to satisfy the heat deficit on the continuous operation (Columns 8 and 9 of Table 6). Construct another seasonal storage cascade for obtaining the changes of EHU requirement during continuous site operation. If there is heat excess at the higher utility level, an additional column could be added to record the heat excess and the heat should be added into the storage cascade. This let-down heat would only be added in the continuous operation's heat storage cascade.
        iii. If the SHS is equal to zero (SHS = 0) during the start-up, the EHU requirement and heat storage cascade during continuous processes operation will be the same as during the start-up process.

4. Results and Discussion

The proposed methodology is illustrated using a Case Study involving four units – Processes A, B, C and D. The stream table of these units are shown in Table 1. According to the availability of streams as in Table 1, three TSLs can be identified for this Case Study - 20-06 h (TSL1), 06-17 h (TSL2), and 17-20 h (TSL3). Minimum temperature difference (ΔT_{min}) is assumed at 12 ºC. The utilities available on site are medium pressure steam (MPS) at 220 °C, low pressure steam (LPS) at 130 °C, and hot water system (HW) at 80-50 °C. Long term variation is also identified for the Case Study, whereby all processes are assumed to operate during the hot season (235 d) and Process C is not running during the cold season (130 d).

During the hot season, renewable energy is available in two periods, i.e., during the normal sunny days with wind blowing (Seasons 2 and 4) and during the cloudy days without wind blowing (Season 3). Season 2 occurs for the first 100 d of a long term cycle. Then, Season 3 occurs for 80 d, followed by Season 4 for 55 d before the onset of the cold season. Note that, the renewable energy sources are not available in the cold season (Season 1). Table 2 shows the renewable energy availability for the TS system in this Case Study.

Table 1: Stream Table for Illustrative Case Study – after (Varbanov and Klemeš, 2011)

Stream	Initial Temp., T_S (°C)	Target Temp., T_T (°C)	Heat duty, ΔH(kW)	Heat capacity, mCp / Latent Heat, H_L (kW/°C)	Shifted Initial Temp., T_S' (°C)	Shifted Target Temp., T_T' (°C)	Time Slice, TSL (h)
				Process A			
A1 Hot	110	80	120.00	1.3330	104	74	00-24
A2 Hot	150	149	180.00	180.00	144	143	00-24
A3 Cold	50	135	104.40	1.2280	56	141	00-24
A4 Cold	85	100	82.30	5.4870	91	106	00-24
A5 Cold	62	100	130.00	3.4210	68	106	00-24
A6 Hot	92	55	130.00	7.6470	86	49	00-24
				Process B			
B1 Hot	200	195	160.00	32.000	194	189	06-20
B2 Hot	20	54	10.00	0.2941	26	60	06-20
B3 Hot	50	85	107.30	3.0657	56	91	20-06
B4 Cold	100	120	130.00	6.5000	106	126	06-20
B5 Cold	150	40	83.50	0.7590	144	34	06-17
B6 Cold	80	95	48.00	3.2000	86	101	06-20
B7 Cold	95	25	80.00	1.1430	89	19	06-17
				Process C			
C1 Hot	85	40	23.85	0.5300	79	34	06-17
C2 Hot	80	40	96.40	2.4100	74	34	06-17
C3 Cold	25	55	17.30	0.5760	31	61	20-06
C4 Cold	55	85	18.00	0.6000	61	91	20-06
C5 Cold	33	60	12.00	0.4460	39	66	00-24
C6 Cold	25	60	15.00	0.4290	31	66	06-17
C7 Cold	82	121	34.10	0.8740	88	127	20-06
C8 Cold	25	28	23.10	7.7000	31	34	06-17
C9 Cold	80	100	32.00	1.6000	86	106	06-17
C10 Cold	18	25	41.10	5.8640	24	31	00-24
C11 Cold	21	121	5.00	0.0500	27	127	06-17
				Process D			
D1 Cold	15	25	88.00	8.8000	21	31	00-24
D2 Cold	15	45	25.00	0.8333	21	51	00-24
D3 Cold	15	45	65.00	2.1667	21	51	06-20

Table 2: Renewable energy availability for all seasons

Season	1			2			3			4		
TSL	i	ii	iii	i	ii	iii	i	ii	iii	i	ii	iii
LPS (kW)	-	-	-	1,000	1,830	700	-	-	-	1,000	1,830	700
HW (kW)	-	-	-	-	1,000	-	-	200	-	-	1,000	-

The data for this Case Study is analysed using the numerical methodology (Liew et al., 2012). TS-PTA is used to obtain the process utility requirement at all TSL for the different seasons. Tables 3, 4 and 5 show the TS-HSC of LPS storage system per day for the different seasons.

The result shows that 1,902 kWh/d of heat excess is available at Season 2 and 4 as in Table 4. External LPS from boiler is required by the TS during Seasons 1 and 3. Table 3 shows that the TS system required a total of 1,158 kWh of external LPS at Season 1, while Season 3 needs 1,628 kWh per cycle of TSLs.

As a result, the heat excess available during Seasons 2 and 4are required to be kept in LPS storage system. The stored heat could be used to satisfy the LPS requirement during the Seasons 1 and 3. Tables 6 and 7 show the seasonal TS-HSCs of LPS for this case study. The cascade table illustrates the energy flows between seasons. The initial cascade shows that the SHS is higher than the Total EHU. A new cascade for start-up process is build and ECU is added to Season 2, which ensured the SHS is equal to the total EHU. The start-up operation of the seasonal cycle has 150,599 kWh of heat surplus to be cascaded to the next cycle (Table 7) to satisfy the heat deficit during Season 1. The net LPS excess for a long term cycle is determined at 14,070 kWh in Season 2. The seasonal storage system has reduced the total LPS requirement of 280,805 kWh in Seasons 1 and 3 to a system with a net 10,070 kWh/y of heat excess. The approach has reduced the energy requirement by 100 % and the cooling requirement by 95 %.

Table 3: Total Site Heat Storage Cascade (TS-HSC) of LPS for Season 1

TSL	Heat required	Additional heat supply	Net heat required	Start-up operation			Continuous operation		
				Storage cascade	External Hot Utility	External Cooling Utility	Storage cascade	External Hot Utility	External Cooling Utility
(h)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)
				0			0		
20-06	970	0	-970		970	0		970	0
				0			0		
06-17	-167	0	167		0	0		0	0
				167			167		
17-20	355	0	-355		188	0		188	0
				0			0		
Total					1,158	0		1,158	0

Table 4: Total Site Heat Storage Cascade (TS-HSC) of LPS for Seasons 2 and 4

TSL	Heat required	Additional heat supply	Net heat required	Start-up operation			Continuous operation		
				Storage cascade	External Hot Utility	External Cooling Utility	Storage cascade	External Hot Utility	External Cooling Utility
(h)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)
				0			417		
20-06	1,417	1,000	-417		417	0		0	0
				0			0		
06-17	-144	1,830	1,974		0	-1,902		0	-1,902
				72			72		
17-20	355	700	345		0	0		0	0
				417			417		
Total					417	-1,902		0	-1,902

Table 5: Total Site Heat Storage Cascade (TS-HSC) of LPS at Season 3

TSL	Heat required	Additional heat supply	Net heat required	Start-up operation			Continuous operation		
				Storage cascade	External Hot Utility	External Cooling Utility	Storage cascade	External Hot Utility	External Cooling Utility
(h)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)
				0			0		
20-06	1,417	0	-1,417		1,417	0		1,417	0
				0			0		
06-17	-144	0	144		0	0		0	0
				144			144		
17-20	355	0	-355		211	0		211	0
				0			0		
Total					1,628	0		1,628	0

Table 6: Seasonal Total Site Heat Storage Cascade (TS-HSC) for LPS

Season	Time	Steam required per day	Steam required per season	Initial		Start-up operation		
				Seasonal storage cascade	External Hot Utility	Seasonal storage cascade	External Hot Utility	External Cooling Utility
	(day)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)	(kWh)
				0		0		
1	130	-1,158	-150,599		150,599		150,599	0
				0		0		
2	100	1,902	190,242		0		0	-14,070
				190,242		176,172		
3	80	-1,628	-130,206		0		0	0
				60,036		45,966		
4	55	1,902	104,633		0		0	0
	Seasonal Heat Surplus (SHS)			164,669		150,599		
Total					150,599		150,599	-14,070

Table 7: Seasonal Total Site Heat Storage Cascade (TS-HSC) for LPS (Continued)

				Continuous operation		
Season	Time (d)	Steam required per day (kWh)	Steam required per season (kWh)	Seasonal storage cascade (kWh)	External Hot Utility (kWh)	External Cooling Utility (kWh)
				150,599		
1	130	-1,158	-150,599		0	0
				0		
2	100	1,902	190,242		0	-14,070
				176,172		
3	80	-1,628	-130,206		0	0
				45,966		
4	55	1,902	104,633		0	0
				150,599		
Total					0	-14,070

5. Conclusions

Energy supply and demand fluctuations in processing plants cause long and short-term variable energy supply and demand in a TS system. Seasonal TS-HSC is proposed in this paper to handle the energy fluctuations.Application of the technique on a case study shows that there is a 100 % opportunity to save the LPS heating through a seasonal energy storage system. On the other hand, there is potential to reduce energy wastage by 95 %. However, further studies are needed to investigate the feasibility of having a huge capacity seasonal storage system and effective heat loss prevention strategies.

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