Absorption Cycle Heat Pump Integration for Locally Integrated Energy Sector

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Abstract. Energy losses in daily life has caused energy inefficiency whereby contributed to serious environment impacts such as carbon emission, greenhouse effect and global warming. The increasing of greenhouse gases emission and crude oil usage have become a main focus to improve world energy efficiency. In order to minimizing the emissions and environmental pollution, Process Integration (PI) through Pinch Analysis (PA) is used to increase the energy efficiency. Total Site Heat Integration (TSHI) is integrated several processes with the centralized utility system. TSHI is extended to Locally Integrated Energy Sectors (LIES) whereby it provides energy integration with end users from various sectors such as the industrial, services, residential, agriculture, transportation and public sectors within a local area, as well as the integration of renewable energy sources. In order to handle the intermittent steam, energy storage is proposed for recovering energy across time period. In this study, waste heat recovery system by using absorption cycle heat pump is highlighted. Two types of absorption cycle heat pump such as absorption heat pump (AHP) and absorption heat transformer (AHT) are used to integrate with LIES utility system to maximize the energy recovery. This new methodology deals with the amount of AHP and AHT heat generation from the enthalpy of working fluid pair in water-lithium bromide with heat storage system in LIES. An illustrative case study is performed for demonstrating and verifying the proposed framework, whereby waste energy recovery opportunities are found from the system studied. Economic analysis on payback period is also performed to compare with the system with and without usage of AHP and AHT. This developing methodology provides a better guidance to engineers especially during the design stage on the performance limitations and specific compromises within a system. At the end of this research, cost saving is achieved, a shorter payback period than existing system and overall energy efficiency is improved within heat storage system for LIES by adding in the absorption heat pump cycle.

1. Introduction

Fossil fuel sustains the most significant energy demands around the world. Since the 1900s, the world demand for fossil fuels nearly doubles after every 20 years [1]. However, it has numerous harmful effects on the climate and living species. Heat integration is vital to improve energy efficiency and reduce
operational costs in the energy related applications such as carbon capture in power plants. Heat integration is also frequently used through integrating a heat exchanger network (HEN) into a process system for waste heat recovery [2]. In the early of 1990, Total Site Heat Integration (TSHI) has started to catch more attentions [3]. TSHI is introduced to integrate a single process in the internal process heat recovery with a centralized utility system [4]. TSHI has been widely used in different industrial sites including places that involved different commercial energy consumers. LIES is a concept to improve the energy efficiency by satisfying all of the heat demands between industry, residential, renewable energy within local area [5]. The energy efficiency in LIES can be obtained by calculating the overall utility requirement and utility cost of the in a local area.

There are many techniques used for energy recovery nowadays. Heat pump is one of the waste heat recovery technique that famous among researchers and engineers. A novel methodology on integrating absorption chiller and electric chiller in district cooling with LIES is introduced [6]. Subsequently, a comprehensive framework in integration of two different types of open cycle heat pumps is introduced for Total Site heat recovery system [7]. Besides that, a new framework has introduced by crossing heat pump inside a system consisting of spray dryer [8]. A review paper is published on reviewing the integration of heat pump in industry site by using Grand Composite Curve (GCC) [9]. Meanwhile, a new framework is introduced to recover waste heat in an industrial plant on conventional heat pump and Joule Cycle integration [10].

Next, with the help of AHT, it has shown an increase of waste heat temperature in an industrial application [11]. A review paper has reviewed few types of AHT and AHP and its corresponding applications on recovering waste heat in industrial site [12]. A novel methodology is introduced to reduce heat loss by using a serial of AHP in district heating for waste heat recovery [13]. An integration of AHP in a solar thermal power plant for cogeneration is introduced [14].

In this research, the comparison of two absorption cycle heat pump systems in LIES for direct incorporation with the utility system is presented as shown in Figure 1. This study explores the effective utilization of Absorption Heat Pump (AHP) and Absorption Heat Transformer (AHT) in LIES methodology. The combined impact of both AHP and AHT systems and sequence of both AHP and AHT are also studied in this study. The study is used to compare best within the few scenarios proposed in case study based on the reduction of utility consumption and simple payback period.

2. Methodology

A new methodology is proposed to increase the energy efficiency in a local area from locally integrated energy sector by integrating absorption cycle heat pump as shown in Figure 2. The impacts of process integration, heat storage system and absorption cycle heat pumps for LIES are investigated. Firstly, heat integration such as PTA, MU-PTA and TS-PTA are used to improve the energy efficiency by a centralized utility system through boosting the recovery of waste heat in several processes within a local area. Then, the base case after TS-PTA is used to compare the economic analysis with several scenarios. These scenarios include few types integration of heat storage system with Absorption Heat Pump or Absorption Heat Transformer for LIES as shown in Figure 2. This novel framework helps to recover waste heat of a local area with the concept of LIES by using absorption cycle heat pump integration.

2.1. Data Extraction

LIES is a concept to improve the energy efficiency by the overall utility requirement and utility cost to fulfil all of the heat demand between industry and local area. Starting Temperature (T_s), Target Temperature (T_t), Enthalpy (ΔH) and Heat Capacity (C_p) in each stream data are required in this work. Each extracted stream data is rearranged as Time Slide (TSL) [15]. TSL is a method that can overcome the variation and fluctuation of those huge energy data in a large amount of heat integration network.
2.2. Individual Process Pinch Analysis
Pinc analysis is widely used in process integration to reduce toxic gas emission towards the environment. Pinch analysis through heat integration is used to maximize feasible recovery of heat and minimize energy consumption in a process. Problem Table Algorithm (PTA) is used to determine pinch point of each stream for individual heat recovery after classifying each stream data into TSL. The data extracted is shifted from $T_s$ and $T_t$ into a new Shifted Starting Temperature ($T_s'$) and Shifted Target Temperature ($T_t'$) by using a minimum temperature difference from process to another process ($\Delta T_{\text{min,pp}}$). Meanwhile, pinch point is a point used to determine heat source or heat sink in a process. The heat above pinch point indicated as heat sink and the heat below pinch point indicated as heat source. After that, PTA is extended to Multiple Utility Problem Table Algorithm (MU-PTA) [16]. MU-PTA is used to
obtain new pinch point of utility at multiple levels by adding the minimum temperature difference from
utility to process (ΔT_{min,up}).

2.3. Total Site Heat Integration
Total Site Problem Table Algorithm (TS-PTA) is one of the methodologies in Total Site Heat Integration
(TSHI). Individual process pinch analysis is then further extended to TS-PTA by centralising all the
considered utility into a centralised utility system [17]. LIES is introduced to TSHI by integrating heat
from different field such as resident area, industry area and renewable energy in a local area [18]. Besides
that, Total Site Heat Storage Cascade (TS-HSC) is introduced by involving heat storage system in TS-
PTA. Heat energy losses are important when the charging and discharging process from heat storage
system to the processes taken place.

2.4. Heat Recovery using Absorption Cycle Heat Pump
There are many designs of Absorption Cycle Heat Pumps for different purposes. Absorption Heat Pump
also known as type I AHP symbolizes on the usual type of absorption heat pump which is used for heat
amplification. This typical AHP can be used when there are excess high temperature and low
temperature waste heat as inlet to produce a medium temperature heat. Meanwhile, in contrast to a type
I AHP, an Absorption Heat Transformer (AHT) operated in a reverse way. AHT also known as type II
AHP and is used for temperature upgrading. AHT is commonly used to upgrade the medium temperature
waste heat inlet to a higher temperature heat with a by-product of lower temperature heat. There are 4
heat exchangers such as a condenser, generator, absorber and evaporator operated in both AHP and AHT
as shown in Figure 1. The common working medium pair for both AHP and AHT are Lithium bromide
solution as absorber and water as refrigerant.

In absorption cycle, flow ratio, $R$, is defined as the ratio of mass flow rate of strong solution, $m_s$, to
the mass flow rate of refrigerant, $m_r$.

The water property data is used to obtain the enthalpy of water vapor and liquid at different pressures
and temperatures. The enthalpy of liquid water, $h_{w,liquid}$ can be obtained by considering reference
temperature at 0 °C. Meanwhile, the enthalpy of superheated vapor, $h_{w,sup}$ is required as the generator
outlet vapor in AHP and AHT in a superheated state. In this constant pressure case, saturation water
temperature has a lower temperature as compared to generator temperature.

![Figure 3. The general concept of AHP and AHT.](image)

2.4.1. Absorption Heat Pump
Firstly, the heat of generator in AHP is calculated based on the required heat to produce water vapour
at 1 from weak solution at 7 and sensible heat required from 7 to 8 as shown in Figure 1. Secondly, the
heat of absorber is calculated based on enthalpy change of water at 5 from 4 to 5 and sensible heat
transferred at 10 from 5. Thirdly, heat of evaporator is calculated based on enthalpy change of input at
4 from 3. Then, the heat of condenser is calculated based on enthalpy change of output at 1 from 2.

2.4.2. Absorption Heat Transformer
The calculation of heat of evaporator and condenser in AHT are similar to AHP. The heat of generator
in AHT is calculated based on energy required to produce water vapour from 6 to 1 and sensible heat
from 6 to 7 as shown in Figure 1. Meanwhile, for heat of absorber in AHT is calculated based on enthalpy change of water changes at 4 to 5 and sensible heat required from 10 to 5.

2.5. Economic Analysis

An economic analysis is divided into total utility cost saving and payback period. First part is to analyse total cost saving from all the considered utilities. Natural gas consumption for boilers, heaters and absorption chillers and electricity consumption for cooling towers are considered during this calculation. Price of natural gas consumption for steam boiler, gas fired heater and electricity consumption for cooling tower are considered as 302.21 USD/kW.y, 249.32 USD/kW.y and 28.45 USD/kW.y from Reference (7). Meanwhile, for second part, equipment cost for AHP, AHT and heat storage system and total utility cost saving from the first part are considered to calculate for the payback period. The equipment cost of AHT, AHP and heat storage are considered as 275 USD/kW heat output, 270 USD/kW heat output and 9.43 USD/kW [19]. The higher the payback period indicates that it takes longer time for this project investment to recover back in terms of profits.

3. Case Study

A case study is demonstrated in this novel methodology for integration of AHT or AHP with LIES. It is used to compare the economic analysis on total utility cost saving and payback period at the end of this research. There are five scenarios proposed including one base case and four different cases with integration of absorption heat cycle pumps into LIES. In this work, a local area including three industrial processes, and additional of residential area for the existing TS system. The stream data that extracted for this study is modified based on the case study from Reference (17) by adding TSL for each utility. All the four processes are considered \( \Delta T_{\text{min,pp}} \) and \( \Delta T_{\text{min,up}} \) of 20 °C and 10 °C respectively. Meanwhile, for site utility specification, High Pressure Steam (HPS) of 272 °C, Medium Pressure Steam (MPS) of 220 °C, Intermediate Pressure Steam (IPS) of 180 °C, Low Pressure Steam (LPS) of 130 °C, Hot Water (HW) of 50 °C, Cooling Water (CW) of 30 °C and Chilled Water (ChW) of 8 °C are used to handle the process intermittency of each stream.

Scenario 1 showed a base case that used to compare total utility cost saving with other scenarios without heat storage system, AHT or AHP. Then, Scenario 2 and 3 involved in the integration of absorption cycle heat pumps without thermal energy storage on AHP and AHT respectively. Besides that, Scenario 4 showed both of these scenarios covered heat storage system and AHP system. Meanwhile, Scenario 5 involved heat storage system and AHT system.

3.1. Total Site Heat Integration

Table 2 showed the summary of Scenario 1 in all energy demands after the steps of TS-PTA. There are positive and negative values in Table 2. Positive value indicated that there are lacking energy for each energy demands. Meanwhile, for negative value, it indicated that it has excess energy for the particular demands. For Scenario 4 and 5, LPS is chosen to undergo TS-HSC as LPS is the only steam that consisted of both positive value and negative value in the Table 2. The lacking energy of positive value shown in TSL 1 is considering the discharging rate of 42 % in heat losses and the excess energy of negative value shown in TSL 2, 3 and 4 are considering a charging rate of 20 % in heat losses. After considering charging and discharging rate, storage at LPS level showed an excess of 84.324 MWh in the TSL 2.

3.2. Waste Heat Recovery by using Absorption Cycle Heat Pump

Table 3 showed the summary of all the energy demands from Scenario 1 to 5. The methodology used in this study is calculated in TSL 1, 2, 3 and 4 as shown in Table 2. Therefore, there are slightly variance in Table 3 as Table 3 showed the summary of total TSL 1, 2, 3 and 4 in 24 hours.

In this study, IPS and LPS utility demands from case study are focused to be fulfil. For Scenario 2, all the heat demands in IPS and LPS from Table 2 is fulfilled by 2 AHP systems. The first AHP is used
in TSL 1, 2, 3 and 4 to generate IPS from waste heat and the second AHP system is used in TSL 1 only to generate LPS from waste heat. The payback period for this case is 4.28 years.

In Scenario 3, there are excess LPS in TSL 2, 3 and 4 as shown in Table 2. Therefore, first AHT is used for excess LPS to generate IPS in TSL 2, 3 and 4. From here, TSL 2 and 3 showed excess IPS from the first AHT used. The second AHT system is used to generate medium pressure steam from excess IPS. The results calculated are then shown in Table 3. MPS usage has been reduced by using AHT. Moreover, the payback period in this case showed 89.18 years which is very high due to the small amount of cost saving as compared to Scenario 1 at only USD 590,202.88.

Besides that, AHP system is used after TS-HSC in Scenario 4. There are 2 AHP systems used in this case. The first AHP system is used to fulfill the IPS demands in TSL 1, 2, 3 and 4 by using LPS and MPS. Then, the second AHP is used when there are demands of LPS in TSL 1, 3 and 4 after first AHP used. Therefore, TSL 1, 3 and 4 has fulfilled LPS demands by using MPS and HW. The payback period in Scenario 4 is 1.02 years. This is due to the involving of the cost of storage in the system.

In Scenario 5, AHT system is used after TS-HSC. Only one AHT used in TSL 2 to produce IPS and CW from excess LPS. As shown in Table 3, the payback period in Scenario 5 is the smallest at 0.37 year. This is because only 1 AHT system is used of excess LPS in TSL 2 and therefore the equipment cost in Scenario 5 is very little as compared to other cases.

In this case study, Scenario 2 and 3 are used to compare the better version of integration AHT or AHP in the study. Scenario 2 which only used AHP system without heat storage system showed better as compare to Scenario 3. This is because Scenario 2 showed more efficient in total utility cost saving as shown in Table 3 and therefore reduced the payback period in Scenario 2. Then, Scenario 4 and 5 are used to compare the better version of integration AHT or AHP into the case study after TS-HSC. This is because the equipment cost of Scenario 4 is very high as compare to Scenario 5. Besides that, there is a big difference between Scenario 3 and 5 in payback period by adding a storage system on 89.18 years and 0.37 years respectively. In this case, storage system is important to reduce the usage of process utility.

### Table 2. Summary of all the energy demands from Scenario 1 after TS-PTA

| TSL | Time        | HPS (MWh) | MPS (MWh) | IPS (MWh) | LPS (MWh) | HW (MWh) | CW (MWh) | ChW (MWh) |
|-----|-------------|-----------|-----------|-----------|-----------|----------|----------|----------|
| 1   | 20:00-06:00 | 21.50     | 94        | 114.5     | 176.6     | 42       | 0.00     | 25.2     |
| 2   | 06:00-17:00 | 23.65     | 73.7      | 40.15     | -170.94   | -377.63  | 0.00     | 55.44    |
| 3   | 17:00-18:00 | 2.15      | 6.7       | 3.35      | -17.04    | -36.73   | 0.3      | 5.04     |
| 4   | 18:00-20:00 | 4.2       | 16.4      | 13.7      | -20.08    | -57.46   | 0.6      | 5.040    |
|     | Total       | 51.5      | 190.8     | 171.7     | -31.46    | -429.82  | 0.9      | 90.72    |

#### 3.3. Economic Analysis

In economic analysis, the first part is to calculate the total utility cost saving for Scenario 2 to 5. This calculation does not include the consideration of absorption chiller in because chilled water load remained the same with Scenario 1 after the integration of AHT or AHP in LIES. As shown in Table 3, In second part of economic analysis, payback period is calculated based on the equipment cost divided by total utility cost saving from first part of economic analysis.

#### 4. Conclusion

In this research, a novel methodology by integrating absorption cycle heat pump into LIES is studied. This case study shows that by implementing absorption heat pump has reduced the utility consumption and shorter payback period to the industry. The results showed Scenario 5 is the best to fit in this case study as it uses least amount of AHT system after TS-HSC. Therefore, it has the least in payback period of just 0.37 years. This research is summarized by if there are excess higher temperature waste heat, AHP is used to target the medium temperature heat and when there are excess medium temperature
Table 3. Summary of the energy and cost saving from Scenario 1 to 5 after integration

| Utility | Unit | Scenario 1 (Base) | Scenario 2 (AHP) | Scenario 3 (AHT) | Scenario 4 (storage, AHP) | Scenario 5 (storage, AHT) |
|---------|------|------------------|------------------|------------------|--------------------------|--------------------------|
| HPS     | MW   | 51.50            | 51.50            | 51.50            | 51.50                    | 51.50                    |
| MPS     | MW   | 190.80           | 420.56           | 173.84           | 322.20                   | 190.80                   |
| IPS     | MW   | 171.70           | 0.00             | 186.74           | 0.00                     | 134.86                   |
| LPS     | MW   | -31.46           | -183.88          | 176.60           | -67.35                   | 0.00                     |
| HW      | MW   | -429.82          | -335.47          | -429.82          | -406.50                  | -429.82                  |
| CW      | MW   | 0.90             | 0.90             | -112.40          | 0.90                     | -41.26                   |
| ChW     | MW   | 90.72            | 90.72            | 90.72            | 90.72                    | 90.72                    |
| Boiler Load Changes | MW | 590.60 | 472.06 | 588.68 | 373.70 | 377.16 |
| Heaters Load Changes | MW | -429.82 | -335.47 | -429.82 | -406.50 | -429.82 |
| Heaters Load Changes | MW | 0.90 | 0.90 | -112.40 | 0.90 | -41.26 |
| Cooling Tower Load Changes | MW | 12,298,159 | 590,203 | 64,503,814 | 59,733,201 |
| Total Utility Cost Saving | USD/y | - | 15,730,000 | 52,631,548 | 61,108,979 | 23,695,659 |
| Payback Period | y | - | 4.28 | 89.18 | 1.02 | 0.37 |

Waste heat, AHT is used to produce higher temperature steam. Absorption cycle heat pumps are used to increase the overall energy efficiency by reusing the waste heat generated from industry to a more useful heat. The proposed framework has provided a better practical tool for engineers or researchers to undergo study on optimizing energy efficiency in a more sustainable way. In this work, heat storage system is implemented before both types of absorption cycle heat pump. In future work, the optimization of heat storage system could be done after the absorption cycle heat pump optimization step. This future work will look at the effect of positioning heat storage system with absorption cycle heat pumps on LIES by adding a detailed cost-benefit analysis for optimization process. Besides that, integration of cogeneration system into LIES with corporation of absorption cycle heat pumps also can be a great opportunity to further study.

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