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# Cogeneration Optimisation for Locally Integrated Energy Systems

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Energy Efficiency is proven to be a significant opportunity for industry, cities and society, in general, to save energy costs and harmful gaseous and particulate emissions. Locally Integrated Energy System (LIES) was introduced to promote symbiosis between industry and local area to enhance their overall system energy efficiency. LIES extends Total Site Heat Integration (TSHI) to optimise the energy system for multiple industrial processes as well as other process heat demands in proximity. This paper integrates the TSHI methodology with Power Pinch Analysis (PoPA) to sequentially optimise the thermal and electrical energy in a LIES. A Power Cogeneration Estimation Table is used to systematically identify and determine the amount of power that the thermal energy system potentially generates via backpressure and condensing steam turbines. This work evaluated the thermal and power system based on total utility cost, where the thermal requirement is fulfilled by the industrial boiler system with the potential of outsourced power demands. A case study is performed for verifying the proposed methodology. Results found that LIES with Heat and Power Integration and battery storage is recommended for low utility cost operation without the need for a heat storage system.

## 1. Introduction

Global energy demand is increasing, which leads to Green House Gases emissions. Therefore, the idea of energy conservation is necessary to mitigate climate change through improving energy efficiency or reducing energy demand. Integrated Energy Contracting (IEC) concept is proposed to reduce final energy demand of a building through various energy-efficient measures and ensure efficient energy supply for the remaining energy demand through prioritising the usage of renewable energy (Bleyl-Androschin, 2011). In a bigger context, the energy-saving measures can be executed not only within a building but between various facilities through energy integration concept called Locally Integrated Energy Sector (LIES).

For heat integration of a local area, Total Site Heat Integration (TSHI) proposed by Dhole and Linnhoff (1993), which is an extension of Pinch Analysis concept, can target the maximum heat recovery potential of several processing plants through a central utility system. The LIES extends the TSHI concept to integrates all types of energy supply and energy demand in a local area consisting industrial site, residential areas and service buildings (such as hospitals, hotels and sports complex) with industrial processes (Perry et al., 2008). The concept considers renewable energy sources and conversion technologies to reduce primary energy consumption and improve energy efficiency. The integration of Power-to-heat and renewable energy is beneficial for overall energy savings (Bloess et al., 2018). The Site Utility Composite Curve (SUGCC) developed by Klemeš et al. (1997) provides the analogous insight of the cogeneration potential of the central utility system by using steam turbines. The heat storage system has been integrated into TSHI for covering unsteady energy supply and demand (Liew et al., 2014), which the excess thermal energy is stored and used at a later time when it is required. Liew et al. (2018) extended that concept to handle long- and short-term variable heat supply and

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demand via thermochemical energy storage. A generic calculation of heat charging and discharging efficiencies are included in the proposed methodology.

Power Pinch Analysis (PoPA) has been introduced for a hybrid power system based on the Total Site concept where the variable power supply and demand are overcome by using power storage (Mohammad Rozali et al., 2013). PoPA integrates renewable energy sources into the conventional energy system. Ho et al. (2012) introduced the Electric System Cascade Analysis (ESCA) based on a distributed energy system concept. Energy losses for charging and discharging the electricity storage system are considered in the analysis. Load shifting has been an essential element in the system design to reduce the power demand at peak hours (Mohammad Rozali et al., 2015), which has a higher grid power price. Lee et al. (2014) proposed a mathematical model for the hybrid power system, which considers energy loss within the system. An extension was done to consider Hydrogen storage system in Hybrid Power System (Janghorban Esfahani et al., 2016). A new multi-objective mathematical model for optimising both off-grid and on-grid system is proposed by Lee et al. (2019).

This paper integrates TSHI and PoPA to optimise the thermal and power energy in a LIES including turbine systems as well as heat and power storage systems, as shown in Figure 1 (after Perry et al., 2008). A systematic tool is introduced to determine the type of steam turbine required for the system and targeting the amount of power that can be cogenerated from the system. This LIES model is studied with various system configurations is presented to portray the importance of power cogeneration and its impact on the system to achieve LIES's energy savings objective.

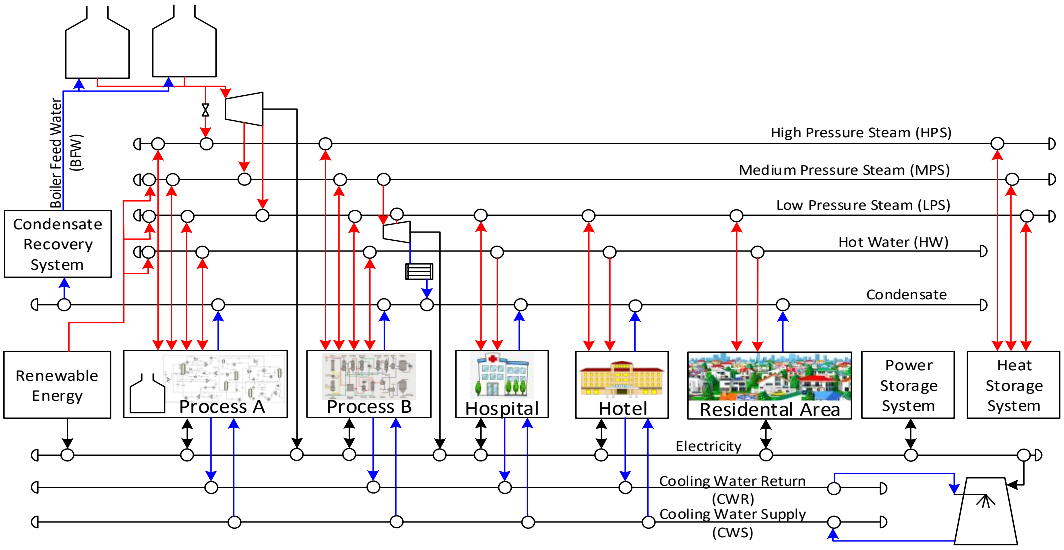


*Figure 1: Locally Integrated Energy Sector with renewable energy and storage systems (after Perry et al., 2008)*

## 2. Methodology

This research proposes a comprehensive framework to optimise heat and power for a LIES, as shown in Figure 2, which combines TSHI and PoPA through heat storage and power storage. The solution methodology caters the fluctuation of heat and power supplies and demands with time. Heat integration is performed to identify the heat demand. This heat demand is the input data required to estimate the power cogeneration potential. This cogenerated power is integrated into the local power network to fulfil the power demand. Both heat storage and battery storage are also considered for further energy demand reduction.

### 2.1 Heat Pinch Analysis for Individual Process and Total Site

The concept of Time Slices (TSLs) extended from the Batch Heat Integration (Klemeš et al., 2018) is used for analysing the variable heat supply and demand. The energy supply and demand are combined to determine the TSLs according to Time Slices Model (Kemp and Deakin, 1989). The energy recovery of individual process and TS are studied according to the TSLs as proposed by Liew et al. (2014), which the energy requirement for each individual processes are determined. The Total Site utility requirement is then determined by TSHI methodology using either a graphical (Klemeš et al., 1997) or numerical approach (Liew et al., 2014).

Heat storage is beneficial for recovering energy across time. The Total Site Heat Storage Cascade (TS-HSC) is used to estimate the energy target with a heat storage system. The heat storage system could be sensible heat, latent heat or thermochemical heat storage. However, the technical feasibility of thermo-chemical heat storage is yet to be proven for efficient use in the industrial process.

The amount of potential excess or waste process heat, which can be used for steam generation through waste heat boiler, is determined with the TSHI and the TS-HSC methodologies. The methodologies are also able to determine the amount of steam to be let down from the boiler pressure to the desired steam header pressures.

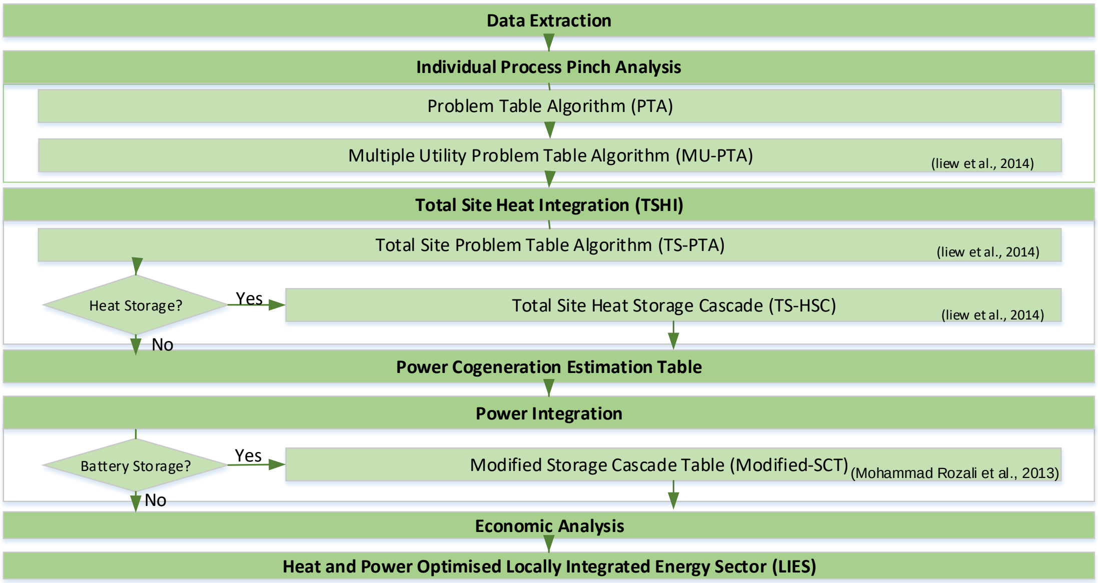
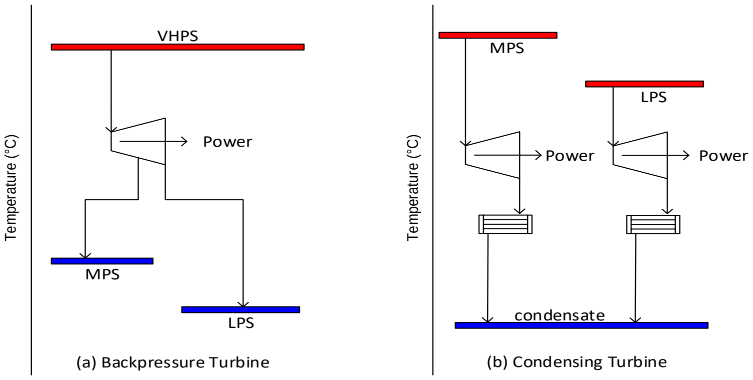


*Figure 2: The proposed LIES methodology for heat and power optimisation*

## 2.2 Power Cogeneration Estimation Table

Turbines are a pivotal link between heat and power analysis in this study. Backpressure and condensing steam turbines are considered in this study, as shown in Figure 3. A backpressure turbine is used for power recovery from expanding higher pressure steam to a lower pressure, while the condensing turbine is involved in energy recovery from waste steam to a condenser under high vacuum.

Process steam demand determines the amount of steam that can be expanded via turbines, cogenerating power, as shown in Figure 3(a). The excess low-grade heat in different TSLs indicates the amount of steam that could be expanded through a condensing turbine to generate power, as shown in Figure 3(b). A Power Cogeneration Estimation Table is used to estimate the power generation from both turbine types.



(a) Backpressure Turbine

(b) Condensing Turbine

*Figure 3: Backpressure and condensing steam turbines*

## 2.3 Power Integration

A typical Power Integration in this study represents by matching the power supply and demand in the power system. The use of battery storage is proposed to tackle the intermittency and dynamic behaviour of renewable energy, such as solar, wind and biomass, known as Power Pinch Analysis (PoPA). The methodology determines the amount of outsourced electricity required to fulfil the power demand of a local area after prioritizing the use of renewable energy. This methodology has been extended into a modified Storage Cascade Table (modified SCT) by Mohammad Rozali et al. (2013) to determine the amount of outsourced electricity and the battery storage required with the consideration of various energy losses during the process such as charging and discharging losses from the battery.

### 2.4 Economic Analysis

The total energy requirements are evaluated in economical cost. The utility cost for thermal and power demand is calculated according to the energy price structure in Malaysia.

## 3. Case Study

A case study is presented to illustrate the framework proposed. The heat demand for the case study consists of industrial plants, hotel and residential area (Liew et al., 2014), while the power demand comes from the residential area (Ho et al., 2012). Wind energy, biomass energy and solar energy are assumed to be available in the case study (Wan Alwi et al., 2012). The case study is analysed under 6 scenarios (Table 1).

*Table 1: Summary of the system specification for all the scenarios*

| Scenario | TSHI | Heat Storage | Steam Turbine | Power Integration | Battery Storage |
|---|---|---|---|---|---|
| 1 | ✓ | X | X | X | X |
| 2 | ✓ | X | ✓ | X | X |
| 3 | ✓ | X | ✓ | ✓ | X |
| 4 | ✓ | X | ✓ | ✓ | ✓ |
| 5 | ✓ | ✓ | ✓ | ✓ | X |
| 6 | ✓ | ✓ | ✓ | ✓ | ✓ |

The Individual Process Pinch Analysis and the TSHI are performed for all scenarios, while TS-HSC is undertaken for only Scenarios 5 and 6. From TSHI, the net energy demand can be determined from TS above Pinch Region while the net energy excess can be obtained from the TS below pinch region. The results obtained are used to estimate the potential power cogeneration, as shown in Table 2. In Table 2, Heat Duty (Q) is the net energy required by the system at each TSL for each utility level, which is Medium Pressure Steam (MPS) and Low-Pressure Steam (LPS). The net energy excess is indicated with a negative sign because it is the waste heat required to be cooled off from the system. Thus, it can be used to generate steam and cogenerate power through condensing turbine, as shown in TSL 2 in Table 2. For net energy demand, it is indicated with a positive sign because it is the required energy demand to be fulfilled by the site boiler system. Therefore, the configuration of the boiler connected with backpressure turbine is chosen to cogenerate power and obtain the required utility steam for the energy demand, as shown in TSL 1 in Table 2.

*Table 2: Power Cogeneration Estimation Table*

| TSL | Duration (h) | $Q_{MPS}$ (kW) | $Q_{LPS}$ (kW) | Turbine Connected Utility | | Power Generation | |
|---|---|---|---|---|---|---|---|
| | | | | Backpressure | Condensing | Power (kW) | Total Energy (kWh) |
| 1 | 10 | 1.72 | 50.35 | MPS, LPS | - | 6.709 | 67.093 |
| 2 | 11 | 0.15 | -199.78 | MPS | LPS | 42.906 | 471.962 |
| 3 | 3 | 0 | 23.28 | LPS | - | 3.047 | 9.140 |

The energy demand and utility cost of the case study are summarised in Table 3 and 4. The heat energy requirement is divided into heating and cooling utilities as targeted in TSHI. The cogeneration potential includes the amount of waste heat that can be used to cogenerate electricity by using a condensing turbine, as illustrated in Figure 3(b). On the other hand, the amount of heating utility is the total amount of heat required to produce by site boiler system to fulfil the total heat demand in the form of MPS and LPS and cogenerate electricity by using backpressure turbine, as shown in Figure 3(a). The natural gas cost (1.41 Ringgit Malaysia (RM)/kg) to fulfil the boiler load with a boiler efficiency of 80 % is calculated for the financial analysis of heat energy demand. The utility requirement for power demand is the outsourced electricity cost from National Grid provider (TNB, 2019) with the tariff of 0.3550 RM/kWh during peak period (8 am to 9 pm) and 0.2190 RM/kWh during the off-peak period (10 pm to 7 am). During the peak period, an additional maximum demand charge (highest power rating) is applied at 37.00 RM/kW. The outsourced and excess electricity listed in Table 3 is the total electricity purchased from National Grid to fulfil the total power demand per month and the amount of excess electricity that could be sold in the same rate. The Power Demand utility cost (Table 4) is calculated by multiplying the amount of electricity required with its respective electricity tariff on peak or off-peak period and deducting the profit earned during the sales of excess electricity.

*Table 3: Utility requirement comparison for all the scenarios*

| Scenario | Cogeneration Potential (kWh/mon) | Heating (kWh/mon) | Cooling (kWh/mon) | Outsourced Electricity (kWh/mon) | Excess Electricity (kWh/mon) |
|---|---|---|---|---|---|
| 1 | 0.00 | 82,815.32 | 74,675.38 | 12,851.04 | 0.00 |
| 2 | 16,672.90 | 82,815.32 | 74,675.38 | 12,851.04 | 16,672.90 |
| 3 | 16,672.90 | 82,815.32 | 74,675.38 | 3,686.20 | 7,568.88 |
| 4 | 16,672.90 | 82,815.32 | 74,675.38 | 0.00 | 2,088.76 |
| 5 | 8,207.05 | 74,400.69 | 74,675.38 | 6,605.47 | 1,319.44 |
| 6 | 8,207.05 | 74,400.69 | 74,675.38 | 6,308.58 | 0.00 |

*Table 4: Utility cost comparison for all the scenarios*

| Scenario | Heating Demand (RM/mon) | Cooling Demand (RM/mon) | Power Demand (RM/mon) | Total Cost (RM/mon) |
|---|---|---|---|---|
| 1 | 10,994.31 | 185.49 | 5,958.69 | 17,138.49 |
| 2 | 10,994.31 | 185.49 | 467.09 | 11,646.89 |
| 3 | 10,994.31 | 185.49 | -991.08 | 10,188.72 |
| 4 | 10,994.31 | 185.49 | -741.51 | 10,438.29 |
| 5 | 9,877.21 | 185.49 | 2,870.90 | 12,933.60 |
| 6 | 9,877.21 | 185.49 | 1,381.54 | 11,444.24 |

Based on the summarised result in Table 4, Scenario 1 has the highest utility cost of 17,138.49 RM/mon was the base case of this study. Scenario 2 portrays the potential of power cogeneration, which the sales of these cogenerated power to National Grid successfully cover the 92.16 % of the cost of outsourcing electricity to fulfil the power demand. Among all these scenarios, Scenario 3 has the least total utility cost because the integration of the power cogenerated from TSHI into the local power network without battery helps in reducing 71.31 % of outsourced electricity required compared to Scenario 1. Besides that, the sales of excess electricity in Scenario 3 also managed to cover the power demand cost and bring 991.08 RM/mon of profits to the system. Scenario 4 with battery storage grants the system great flexibility to store its excess electric power and utilise it during power demand. Scenario 4 is able to fulfil the power demand without outsourcing any electricity, and it can even bring profits of 741.51 RM/mon to the system due to the sales of excess electricity. The system configuration of Scenario 4 is more environmentally friendly compared to Scenario 3 because it totally eliminated the need of outsourced electricity from the National Grid which mainly used nonrenewable resources to generate electricity that comes with Green House Gases (GHG). Scenario 5 and 6 shows the 10.16 % reduction in heating utility requirement with the aid of heat storage in the system compared to other Scenarios without heat storage. However, the reduction in heat demand also reduces 50.77 % of the cogeneration potential because less amount of utility steam is required from the boiler system and the amount of waste heat can be condensed reduced as well which lead to higher cost for power demand. Scenario with battery storage can manipulate the time for outsourcing the electricity supply from National Grid, which lowers electricity tariff is available during the offpeak period, and maximum power demand is charged during peak period. Scenario 6 with battery storage has lower power demand cost compared to Scenario 5 because Scenario 6 can outsource electricity at off-peak period and without maximum power demand cost. Scenario 6 supposes to be the best solution to this proposed LIES framework, which the heat and power storage system are available to reduce the amount of heat energy demand and the amount of outsourced electricity. However, the case study shows that Scenario 6 has zero excess electricity and 6,308.58 kWh/mon of outsourced electricity, which lead to a high amount of total utilities cost compared to Scenario 3 and 4. This is due to the excess waste heat is fully recovered via a heat storage system, and no excess electricity for cogeneration and the outsource power cost is higher in this scenario compared to Scenario 3 and 4.

## 4. Conclusions

Heat and Power are integrated into LIES to improve energy efficiency and reduce energy consumption through Total Site Heat Integration (TSHI) and Power Pinch Analysis (PoPA) with power cogeneration potential as the key link in between. The estimation of power cogeneration is determined with a new hybrid method. The importance of power cogeneration is significant in the case study which proves that power cogeneration and its integration into the local power network can save more energy in terms of both thermal and power in a local area to maximise LIES energy efficiency. However, the cost-effectiveness of heat and battery storages are not well demonstrated through the case study in this paper. This is due to the energy excess in the system is not sufficiently high to cope with the losses are the storage system. For future work, the Power Cogeneration Estimation Table could also use an accurate steam turbine model. Robust optimisation is also required to optimise between the amount of heat recovery via heat storage and power recovery via power storage for maximising the cogeneration and minimising the utility cost.

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