# Sequential Thermal and Power Integration for Locally Integrated Energy Sector

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**Abstract**. Energy Efficiency is aligned with the United Nation Sustainable Development Goal for ensuring access to affordable, reliable, sustainable and modern energy for all. Locally Integrated Energy Sector (LIES) concept is introduced for energy conservation between industrial, service and residential sectors. The LIES concept extended the Process Integration technique for energy recovery between multiple process plants through the utility system, known as Total Site Heat Integration (TSHI). However, the development of LIES techniques is divided into two main directions, which are heat and power energy integration. This paper introduces a sequential approach for integrating the heat and electricity system in a LIES. The optimization is done based on time frame, which Time Slices (TSLs) are identified based on drastic changes in heat and electricity supply and demand. The heat system is first analysed by TSHI techniques, which the heat excess and demand are determined. The excess and demand is then used for cogeneration opportunities estimation, which the backpressure and condensing turbine are used. The potential power generation estimated then included to analyse the electricity system using Power Pinch Analysis tools. The use of heat and power storage system are also included in the study, for assessing its impact on the LIES's energy efficiency. The study considered on- and off-grid power supply system to satisfy the power demand of the system. This proposed heat and power optimisation framework aims to select a system configuration with minimal energy cost.

## Introduction

One of the key contributors to climate change is the inefficient usage of energy. The inefficient usage of non-renewable energy will not only cause harm to the environment but will also be wasting the limiting sources of non-renewable energy. Thus, the improvement in the energy usage pattern in a local area which prioritizes the usage of renewable energy and reduces the energy demand through energy recovery are important measures to ensure energy efficiency.

Process Integration is a process to reduce environmental emissions and consumption of resources. Pinch Analysis is one of the methodologies widely used to target the feasible heat energy recovery to reduce energy consumption [1]. Various researches as extension of Pinch Analysis to conserve or reduce the consumption of other resources such as oxygen [2], water [3], carbon dioxide [4] and hydrogen [5] are also available. In a bigger context, the energy saving through Pinch Analysis can be further advanced into targeting multiple types of energy recovery in a big energy network, which connects all of the buildings in a local area as energy consumers and various sources of renewable energies as energy suppliers together [6]. This concept is called as Locally Integrated Energy Sector (LIES) by Perry et al. [6]. From LIES, there are two main types of energy integration can be connected through energy conversion and energy storage technologies, which are Heat Integration and Power Integration.

For Heat Integration in a local area, Dhole and Linhoff [7] proposed Total Site Heat Integration (THSI), which is an extension of Pinch Analysis to target maximum heat recovery of several process plants in an industrial site. Heat energy storage system can be integrated into the TSHI by using Total Site Heat Storage Cascade (TS-HSC) to further reduce the heat energy demand through storing the excess thermal energy for later time use when it is required [8]. Moreover, long- and short-term variable heat supply and demand can be solved by using thermos-chemical energy storage [9]. Jamaluddin et al. [10] developed multiple energy targeting in terms of power, heating, and cooling based on TSHI.

The Site Utility Grand Composite Curve (SUGCC), developed by Klemeš et al. [11], provides insight on the potential of power cogeneration by using steam turbine in the central utility system. These potential cogeneration power can be integrated into local power network for Power Integration by using Power Pinch Analysis (PoPA). PoPA can tackle the dynamic behavior of electricity supply from renewable energy and integrates it into a conventional system by using power storage [12]. For distributed energy system concept, Electric System Cascade Analysis (ESCA) can be used [13]. Load shifting method is also proposed to reduce power demand at peak hours which has higher grid power price [14]. Janghorban Esfani et al. [15] extended the energy storage methodology to store excess electricity by using hydrogen storage system. Multi-objective mathematical model for optimizing both off-grid and on-grid system is proposed by Lee et al. [16].

To realize LIES concept as shown in Figure 1, this paper sequentially integrates TSHI and PoPA targeting methodologies to optimize the thermal and power systems of a local area through energy storage and steam turbine systems. This framework is important to determine the maximum energy recovery possible in local area to reduce energy demand and improve energy efficiency. The paper considered the on- and off-grid power supply strategy to determine the most energy savings and cost-effective energy system structure for an LIES.

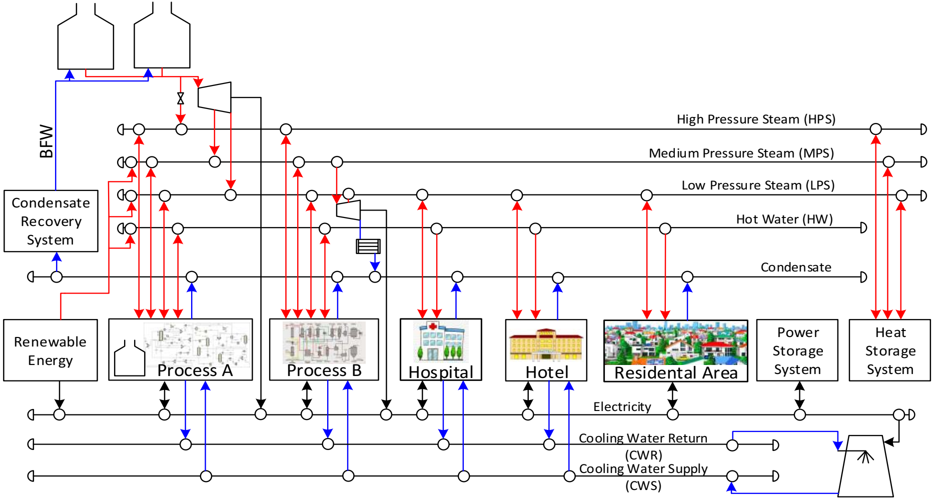


**Figure 1.** Locally Integrated Energy Sector with renewable energy, steam turbine system and storage system after Perry et al. [6]

## 2. Methodology

The proposed framework to achieve thermal and power integration in a local area is as shown in Figure 2. TSHI and PoPA are used to integrate the energy suppliers and users with the thermal storage, power storage, and steam turbine system. Heat integration is performed to determine the heat demand. Thermal storage is also considered to further reduce the heat demand. Then, the power cogeneration potential by using steam turbine is estimated. This cogenerated power is used as electricity source together with renewable energy to fulfil the power demand. Battery storage is also integrated into the system to cater the fluctuation in energy demand and supply through storing and discharging electricity for later use.

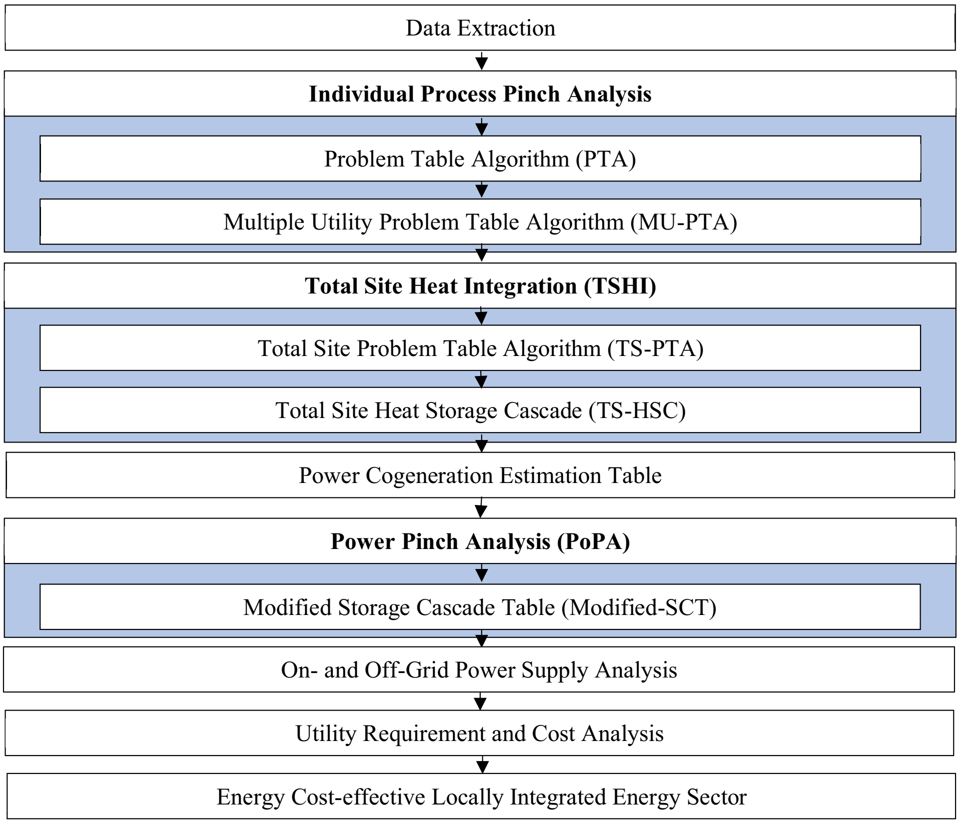


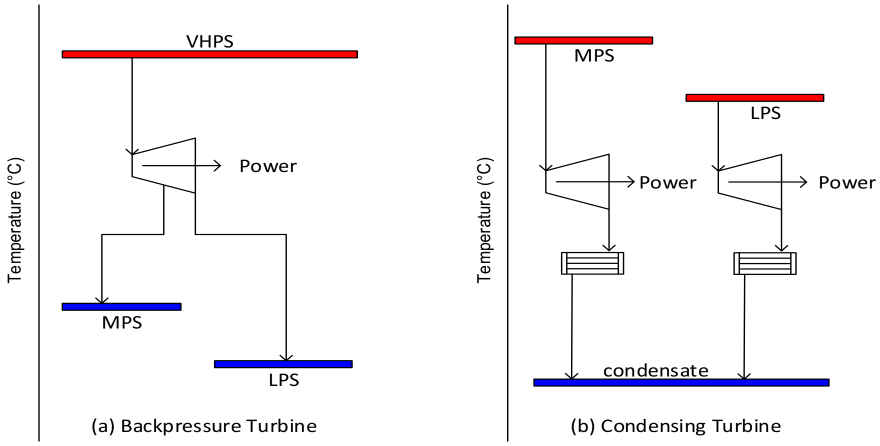
**Figure 2.** Framework for sequential thermal and power integration for Locally Integrated Energy Sector.

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

The Time Slices (TSL) methodology proposed by Nemet et al. [17] is used to specify time intervals to deal with variation and fluctuation of the large amount of energy data involved in the network. Based on each TSLs, the energy recovery of each process are analyzed by using pinch analysis to determine the pinch point, which will separate the process into heat sink and heat source. The energy requirement at multiple utility level is determined as proposed by Liew et al. [18]. It is further developed into TS which is the combination of all of the individual process together through central utility system. The central utility system’s utility requirement can be determined by using Total Site Heat Integration (TSHI) in either graphical [11] or numerical approach [18]. The further reduction in energy demand is possible by using heat storage to store excess energy for later use. Thus, Total Site Heat Storage Cascade (TS-HSC) is used to determine the energy target with a heat storage system [8]. Heat storage can be catagorized into sensible heat, latent heat or thermos-chemical heat storage [19]. However, the technical feasibility of these heat storage to be applied in the industry in large scale is still yet to be proven efficient. Based on the utility requirement at multiple levels, the amount of waste heat to be eliminated from the system, as well as the required amount of steam to be let down from boiler pressure to desired steam header pressures, can be identified easily.

### *2.2 Power Cogeneration Estimation*

Steam turbine as energy conversion technology is the pivotal link between Heat Integration and Power Integration. Backpressure steam turbine can recover the energy during the expansion process of Very High Pressure Steam (VHPS) to lower pressure utility steam such as MPS and LPS and convert the energy into electricity as illustrate in Figure 3(a). On the other hand, for the waste heat to be eliminated from the energy network, the waste heat energy can be recovered and turned into electricity as well by using waste heat boiler connected with condensing turbine as shown in Figure 3(b). A Power Cogeneration Estimation Table is developed to estimate the total amount of power can be cogenerated from both of the steam turbines.



(a) Backpressure Turbine (b) Condensing Turbine

**Figure 3.** Backpressure and condensing turbine.

*2.3 Power Pinch Analysis (PoPA)*

PoPA is used to tackle the intermittency and dynamic behaviours of renewable electricity supply with the help of battery storage. The power demand and power supply are analysed and matched together to determine the required amount of outsourced electricity as well as the excess electricity that can be charged into battery storage at each time interval. Modified Storage Cascade Table as an extension of PoPA takes the various loss of energy during the process such as charging and discharging losses from battery and energy loss for AC-DC inverter into account to estimate the required amount of outsourced electricity at higher accuracy [20].

*2.4 On-Grid and Off-Grid Power Supply Strategy and Cost Analysis*

When the electricity supply from renewable energy and cogenerated power are insufficient to satisfy the power demand, outsourcing electricity from other sources is necessary. There are 2 strategies for power supply can be considered, which are On-Grid power system and Off-Grid power system. On-Grid system is the supply of electricity to the local distribution network through connection with the national grid. When after satisfying the power demand, the excess electricity can be sold to the national grid while when there are insufficient of electricity supply from renewable energy sources, the electricity can be outsourced from the national grid [21]. For Off-Grid system, it can be also known as decentralized power generation, which generates electricity locally by using locally available resources instead of depending on the national grid [22]. Since the steam turbine is invested in this proposed framework to harvest cogeneration power. Thus, it is suggested to further utilize it to self-generate more power to fulfil the power demand by using the idea of Off-Grid system. For comparison purpose, the cost of self-generation of electricity through Off-Grid system is estimated to compared to the cost of outsourced electricity from local national grid network operator through On-Grid system.

## 3. Case Study

A case study is presented to illustrate the energy network of LIES. In this energy network, the main thermal energy consumers are industrial plants, hotel and residential area [8], while the power demand

comes from residential area [13]. The renewable energy supplies available in this case study are assumed to be wind, solar and biomass [12]. The cogeneration potential and utility requirement after the application of sequential thermal and power integration into the local energy system as proposed in Figure 2 are calculated. Then, the effectiveness of the proposed LIES system is compared with a baseline case study, which only considered TSHI without heat storage.
The methodology to analyze the energy demand for both baseline case study and the proposed framework is the same from the beginning of data extraction until TSHI. First, the individual process pinch analysis is essential to locate the pinch point and energy demand at multiple utility level of each facility in a local area by treating them as an individual process through PTA and MU-PTA. Then, the TSHI is performed by using TS-PTA to estimate the required heat demand after recovering heat energy inter-facilities through the central utility system. For the proposed framework, heat storage is added, which can further reduce the heat demand by storing the excess electricity for later use. For this case study, the heat storage is assumed to have 20% of heat loss during charging and 42% of heat loss during discharging. Therefore, TS-HSC as an additional step in TSHI is used as shown in the proposed framework.

### *3.1 Power Cogeneration Potential Estimation*

As proposed in the framework, the heat demand calculated from TS-HSC is used to estimate the amount of power can be cogenerated from the heat integration by using the newly developed tool as shown in Table 1. Heat Duty (Q) is the net energy required to fulfill the heat demand at each TSL for each utility level, which are MPS and LPS in this case study. The negative heat duty is the amount of excess heat required to be cooled off from the system. Thus, these waste heat can be used to generate steam and cogenerate power by using condensing turbine as shown in TSL 2 in Table 1. On the other hand, the positive heat duty indicates the required heat demand to be fulfilled by using site boiler system. Therefore, power cogeneration is possible by using the configuration of site boiler connected with backpressure turbine as shown in TSL1 in Table 1. Hence, this new tool can ease the identification of steam turbine type required by the system and the estimation of amount of power cogeneration. Based on Table 1, a total power of 2,791.52 kWh per month can be cogenerated and integrated into the local power network.

**Table 1.** Power cogeneration potential estimation.

| 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 | 0 | MPS | - | 0.113 | 1.134 |
| 2 | 11 | 0.15 | -45.41 | MPS | LPS | 8.240 | 90.642 |
| 3 | 3 | 0 | 0 | LPS | - | - | - |
| | | | | Power Cogenerated (kWh/day) | | | 91.776 |
| | | | | Power Cogenerated (kWh/month) | | | 2,791.52 |

### *3.2 Utility Requirement*

The utility requirement in terms of Heating, Cooling and Outsource Electricity of the local energy network are tabulated in Table 2. The comparison between Baseline and Proposed Framework (On-Grid) showed a reduction of 32.73% in the heating demand, which proved the potential of heat storage to recover heat energy across time. Thus, lesser utility steam is needed for heat demand, which will also reduce the consumption of natural gas to generate it. The utilization of excess heat to cogenerate power by using a condensing turbine also helped to reduce the cooling utility. Therefore, the cooling utility requirement of the Proposed Framework is 2.11 times lesser than the Baseline. Besides that, the integration of cogenerated power into the local power network through PoPA with the aid of battery storage successfully reduced 8.40% of the Outsource Electricity to fulfill power demand. In Off-Grid-Proposed Framework, the Power Demand is fulfilled by self-generating electricity instead of outsourcing electricity from national grid. The electricity is generated from condensing VHPS into condensate by using condensing turbine. Thus, the boiler load is increased by 44,112.82 kWh/month of boiler load is required to generate 12,161.75 kWh/month of electricity. Therefore, Off-Grid Proposed Framework has 2.07 times higher heating utility than On-Grid Proposed Framework and fully independent from outsourcing electricity from the national grid.

Overall, the required total energy to fulfill the heating, cooling and power demand is reduced by using LIES concept as portrayed in the Proposed Framework, which proved the effectiveness of LIES to reduce energy consumption. The overall energy required by Off-Grid Proposed Framework is higher than On-Grid Proposed Framework because the energy conversion from heat to electricity is not 1 kWh of heat energy to 1 kWh electricity. The conversion is based on the enthalpy, entropy, and quality of the inlet and outlet steam as well as the steam turbine efficiency.

**Table 2.** Utility requirement for thermal and power.

| Utility Requirement | Heating (kWh/month) | Cooling (kWh/month) | Outsource Electricity (kWh/month) | Total Energy Required (kWh/month) |
|---|---|---|---|---|
| Baseline | 61,086.20 | 103,562.18 | 13,276.88 | 177,925.26 |
| Proposed Framework (On-Grid) | 41.092.61 | 49,078.63 | 12,161.75 | 102,332.99 |
| Proposed Framework (Off-Grid) | 85,205.42 | 49,078.63 | 0.00 | 134,284.05 |

### *3.3 On-Grid and Off-Grid Power Supply Strategy and Overall Utility Cost Analysis*

The outsourced electricity is the required electricity to fulfill the power demand after prioritizing the usage of cogenerated power and renewable electricity supply. The required extra electricity can be obtained through On-Grid or Off-Grid system. On-Grid system is the easier method, which electricity is outsourced from the local national grid operator. In this case study, the local national grid operator in Malaysia is Tenaga Nasional Berhad (TNB). However, there are a lot of energy losses in this method because of low energy efficiency along the process of production of electricity by using coal power plant to the transmission and distribution of electricity to the local consumer through a national grid network. Generally, the energy loss during generation of electricity in a coal power plant is 62% [23] and the electricity lost during transmission from the centralized power plant and distribution to the end-user customer is 17% and 50% [24]. The high energy losses for a centralized national grid network indicates the inefficient usage of primary energy. Thus, an alternative method to produce excess electricity to fulfill the electricity demand is maximizing the utilization of the steam turbine for self-generation of electricity as portray in Off-Grid power system to get rid of dependency on national grid. Natural gas or renewable energy resources such as biogas can be used to produce VHPS by using a site boiler with high energy efficiency. Then, this steam is fully condensed into water by using condensing turbine to generate power. Therefore, the installed steam turbine in the energy network with the original purpose to harvest the excess energy in heat integration and turn it into power can be further utilized for self-generation of electricity as an Off-Grid system.

The economical aspect in terms of overall utility cost of this 2 methods are compared with the Baseline in Table 3. The heating utility cost is based on the cost of natural gas at the rate or RM 0.131/kWh to produce the required utility steam. The cooling utility cost is calculated based on the total amount of electricity required for air cooler at the rate of 0.007kWh electricity per 1 kWh of heat duty. The cost of outsourcing electricity from the national grid can be calculated based on the tariff of RM 0.2190 /kWh during off-peak period (10pm to 7am). During peak period (8am to 9pm), 0.3550 Ringgit Malaysia (RM)/kWh is charged and an additional maximum demand charge (highest power rating) is also applied at 37.00 RM/kW.

Based on Table 3, the Off-Grid Proposed Framework has the highest heating utility cost because Off-Grid system has higher boiler load due to self-generation of electricity, which also leads to zero dependency on Outsourced Electricity from national grid. The usage of condensing turbine for cogeneration successfully maximize the energy in LPS waste heat and turn it into useful electricity source while also reducing the cooling utility. LIES concept with heat and power storage as shown in Proposed Framework successfully reduced the energy demand which also leads to reduction in the utility cost. The On-Grid system has cheaper total utility cost compared to Off-Grid system because the cost of outsourcing electricity from national grid is cheaper than self-generation of the same-amount of electricity by using condensing turbine.

Table 3: Overall Utility Cost

| Utility | Heating (RM/month) | Cooling (RM/month) | Outsource Electricity (RM/month) | Total Utility Cost (RM/month) |
|---|---|---|---|---|
| Baseline | 8,002.91 | 221.41 | 6,108.04 | 14,332.36 |
| On-Grid Proposed Framework | 5,383.54 | 101.69 | 2,663.62 | 8,148.85 |
| Off-Grid Proposed Framework | 11,167.24 | 101.69 | 0.00 | 11,268.93 |

## 4. Conclusion

Sequential thermal and power integration for LIES is successfully achieved by using the proposed framework. Both of the thermal and power demand of the energy network in LIES are reduced with the help of thermal storage and power storage. The power cogeneration through conversion of the waste heat energy from heat integration into electricity by using steam turbine is proven to be important source of energy to be harvested. The integration of these cogenerated electricity into local power network can save more energy in terms of both thermal and power in a local area to maximize the energy efficiency of LIES. The Off-Grid system for self-generation of electricity by using steam turbine has higher cost compared to On-Grid system. However, the Off-Grid system has higher energy efficiency, which is also beneficial to our environment due to lower loss of energy to the environment and lesser emissions of GHG compared to On-Grid system. For future work, more research is required to investigate the methodology to further utilize the waste heat in the cooling demand to reduce the consumption of cooling utility. Moreover, a detailed heuristic is required to determine the configuration of LIES system depending on cases to achieve higher energy saving. The modularity of this large scale energy system should be investigated as well to determine its technical feasibility and its ability to react to a system shock.

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