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OPTIMIZING ENERGY EFFICIENCY: AN INTEGRATED LIFE CYCLE COSTING APPROACH FOR CENTRALIZED COOLING PLANTS

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Abstract
Gas District Cooling (GDC) is an emerging technology utilizing natural gas-based systems for efficient district-scale cooling. This study develops a comprehensive Life Cycle Costing (LCC) model integrating capital expenditure (CAPEX) and operational expenditure (OPEX) for Thermal Energy Storage (TES) and Electrical Chillers (ECs) within GDC plants. Validated through a case study at an academic institute's GDC plant in Malaysia, the model assesses breakeven scenarios, revealing that project feasibility is optimal under case-II conditions, emphasizing the importance of operational efficiency for sustained economic viability throughout the plant's lifespan. These insights enhance understanding of financial considerations and investment strategies for adopting GDC technology in urban cooling applications, highlighting the need for strategic planning and lifecycle management to optimize economic performance and support broader sustainable development goals. Ongoing research will further refine LCC models, advancing the economic competitiveness of GDC as a key component of sustainable urban cooling solutions.
Keywords: life cycle cost, thermal energy storage, OPEX, CAPEX

1. INTRODUCTION

The Gas District Cooling (GDC) plant, located on-site, serves as a power generation facility utilized to produce both electrical energy and chilled water. Natural gas is employed as the fuel for gas-turbine ships to facilitate this production. It is imperative to incorporate additional power sources to effectively manage fluctuations in demand. Historical records underscore the value of energy storage (ES), focusing on cost reduction, optimizing energy consumption, improving indoor air quality, evaluating operational flexibility, and minimizing maintenance costs (Dincer, 2021; Dincer, 2002). Additionally, utilizing natural gas as fuel contributes to an environmentally friendly atmosphere, reducing pollution (Da Chunha, 2016; Barnes and Levine 2011).

Energy storage frameworks can be categorized into two types based on their nature: Mechanical and Hydraulic. Mechanical storage involves transforming power into various forms such as evolution, rotation, or compression energy. Alternatively, energy can be stored using metal hydrides in the form of hydrogen (Palomares et al., 2012). While the Electrochemical approach is considered one of the most efficient ways to store energy, it comes with a higher cost (Chen et al., 2009; Ramzan et al., 2019). Despite these options, the application of thermal storage systems for temperature-related requirements, such as liquid (water) temperature, space, chilled air-conditioning, and others, remains a significant consideration for observation. Primarily, there are two types of Thermal Storage System (TSS) frameworks: Sensible, such as water and rock, and Latent, like ice or water and salt hydrates (Zelba, 2003). The

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selection of an optimal TSS framework depends on factors such as storage time, financial viability, and operational conditions. The TSS framework comprises two main components: electrical chillers and a thermal storage tank. The thermal energy storage tank holds water at different temperatures, with the inflow from the HVAC building system playing a crucial role in monitoring the completion of the water cache system. Various methodologies, including the application of coupled tanks (each for warm and cold water), the division of a single tank to distinguish chilled and hot water, and an integrated approach, have been implemented. Supporting chillers can be employed in conjunction with the thermal energy storage tank to meet heating or cooling requirements.

TES chilled tanks are strategically used to address daytime peak demands by storing energy during nighttime peaks (Khan et al., 2004). The use of gas turbines is explored to achieve excess electrical power production, with availability for co-generation foundry during nighttime. This investigation focuses on employing electrical chillers to produce chilled water, charging the thermal energy storage container. The stored chilled water in the tank supports enhanced daytime peak requirements, ensuring effective electricity utilization. The study demonstrates that TES performance is influenced by the operational capability of the TES system. The investigation observes a system comprising one thermal storage tank and three electrical chillers. To enhance Thermal Storage System (TSS) efficiency, it is crucial to optimize the utilization of the Thermal Energy Storage (TES) tank and Electrical Chiller through effective management facilitated by a collaborative appliance. Therefore, the utilization of Life Cycle Costing (LCC) has been extensively monitored (Gluch and Baumann, 2004; Akbar, 2021). LCC involves the monetary optimization of any physical resource or asset, considering all budgetary factors related to the asset's utilization throughout its operational life cycle (Ahsan et al., 2019). In comparison to alternative frameworks that can fulfill similar requirements, LCC involves analyzing cash flow by calculating the difference between cash inflow and cash outflow associated with system acquisition and ownership. The study is conducted at the Gas District Cooling (GDC) plant, equipped with gas-turbine ships responsible for power production (Ahsan and Lemma, 2017; Akbar and Mokhtar, 2017), along with Electrical Chillers and TES tanks. Static parameters, selected either during installation or the feasibility study, serve as the foundation for predicting the monetary or cost aspects in current life cycle costing models. However, the costs associated with Thermal Energy Storage (TES) tanks and Electrical Chillers are not constant due to the variability in operational costs and the need for chilled water production (Soomro et al., 2018, Fallek, 1986). In the real-world context, procedural costs may fluctuate based on electricity assessment utility charges. Additionally, variations in maintenance costs encompass both corrective and preventive maintenance expenditures. The longevity and feasibility of the framework may undergo changes when costs fluctuate (Akbar et al., 2021).

Hence, this study aims to anticipate cost fluctuations by employing a dynamic approach in Life Cycle Costing (LCC). This methodology, previously unused for thermal storage systems, instills confidence in the authors. Consequently, the investigation focuses on efficiently developing the cost of the thermal storage system and assessing changes in demands through a dynamic LCC model.

2. METHODOLOGY

This research primarily focuses on the Gas District Cooling (GDC) plant at an academic institute, Malaysia, to assess a dynamic approach-based Life Cycle Cost (LCC) model, considering the presence of Thermal Energy Storage (TES) tanks and Electrical Chillers. The methodology initially adopts a fundamental LCC simulation, combining the operational dynamics of the thermal energy storage system and electric chillers at the specified GDC plant. Subsequently, this fundamental model is transformed into a dynamic one. The Net Present Value (NPV) concept is employed to calculate the LCC, utilizing a MATLAB model. The model assumes that the appliances do not resist aging, and their replacement occurs at the end of their lifespans. The establishment of this simulation is based on the availability of TES tanks and Electrical Chillers at the academic institute's GDC plant. The developed model spans a duration of thirty years, with key equations demonstrated in Equation 1 and Equation 2 (Hudson, 2000).

$$\boldsymbol{NPV_{Fv}} = [\mathbf{1} \div (\mathbf{1} + \boldsymbol{i})^{\boldsymbol{N}}] \times \boldsymbol{FV} \qquad \textbf{\textit{Equation 1}}$$
$$\boldsymbol{NPV_{Av}} = [\{(\mathbf{1} + \boldsymbol{i})^{\boldsymbol{N}} - \mathbf{1}\} \div \{\boldsymbol{i} \times (\mathbf{1} + \boldsymbol{i})^{\boldsymbol{N}}\}] \times \boldsymbol{AV} \qquad \textbf{\textit{Equation 2}}$$

Where.

$i = shows\ interst\ rate$

$N = shows\ no{:}\ of\ years$

The evaluation of Costs and Revenues is conducted by combining the two equations, referred to as Eq:1 and Eq:2, resulting in Eq:3, which forms the foundation of the adopted Life Cycle Cost (LCC) model. Therefore, Equation 3 is expressed as

$$\boldsymbol{LLC = Total\ Revenue - Total\ Cost} \qquad \textit{Equation 3}$$

The revenue charges encompass earnings derived from the sale of chilled water or the salvage value of old equipment. On the other hand, costs include charges associated with both operational expenditures (OPEX) and capital expenditures (CAPEX) for the plant, covering procedural, maintenance, and replacement expenses. The GDC plant at the academic institute provides data on revenues and operational costs. However, the data appears incomplete, requiring estimation of missing values before commencing Life Cycle Cost (LCC) computations. Therefore, several assumptions are made to approximate the remaining values, such as considering average running. Additionally, the available statistics are deemed insufficient for Net Present Value (NPV) analysis, and modifications are made on a yearly basis for LCC computations. The provided details are categorized into two groups: Revenues and Costs, with the objective of simplifying the LCC model. The actual type of NPV considered is both future and annual. The calculation of total revenues and total costs is achieved by summing up the values within each category. The dynamic approach based LCC is then derived by subtracting the total cost from the total revenue, aiding in the analysis of the system.

Here, a set of equations for revenue and cost is utilized to compute values for the thermal storage system, as shown in Equation.4 and Equation.5, respectively.

$$\boldsymbol{Cost_{TSS} = \sum_{i=1}^{m}\sum_{j=1}^{n_{TES}} COST_{TES+} \sum_{i=1}^{m}\sum_{j=1}^{n_{EC}} COST_{EC}} \qquad \textit{Equation 4}$$

Where: $COST_{TES}$ denotes thermal energy storage cost for single tank, sum of it represented by n means number of thermal energy storage systems available while $COST_{EC}$ denotes charges of EC of single and for multiple electrical chillers it can be calculated by multiplying with n means number of electrical chillers exists).

$$\boldsymbol{Revenue_{TSS} = \sum_{i=1}^{m}\sum_{j=1}^{n_{TES}} REVENUE_{TES+} \sum_{i=1}^{m}\sum_{j=1}^{n_{EC}} REVENUE_{EC}} \qquad \textit{Equation 5}$$

Where: $REVENUE_{TES}$ denotes thermal energy storage revenue for single tank, sum of it represented by n means number of thermal energy storage systems available while $REVENUE_{EC}$ denotes earned amount of EC of single and for multiple electrical chillers it can be calculated by multiplying with n means number of electrical chillers exists. Capital expenditures (CAPEX) refer to the amount invested in the installation of the thermal energy storage system, electrical chillers, and other technological mechanisms. Additionally, operational expenditures (OPEX) encompass the costs associated with running the system, such as utility charges and maintenance expenses. In the subsequent section, EC cost and TES cost are initially described separately to highlight the total cost of the Thermal Storage System (TSS).

In this research, EC cost is estimated, as it is missing for all entire capacities. For this estimation, the Power Sizing approach is emphasized, a method commonly used for similar purposes. This approach is calculated by Eq: 6, as follows.

$$\boldsymbol{{COST_{ECa}}/{COST_{ECb}} = \left[{Capacity_{ECa}}/{Capacity_{ECb}}\right]^{x}} \qquad \textit{Equation 6}$$

Where: *a* shows first Electric chiller and *b* shows second EC while *x* used to capacity ratio of cost as it may take 1 if cost relationship assumed as linear.

2.1 Budget Estimation associated with electric chillers

The cost of the electrical chiller can be generally computed using equation 7, which is expressed as:

$$\boldsymbol{COST_{EC_1} = \left[\sum_{i=1}^{n} MC_{i_1} + \sum_{i=1}^{n} OC_{i_1}\right] + C_{I_1}} \qquad \textit{Equation 7}$$

Where; Operational cost= OC, Maintenance Cost= MC and $Cost_{EC_1}$ amount charged on a chiller.
To determine the variable capacities of multiple electrical chillers, the following equation 8 will be utilized:

$$\boldsymbol{COST_{EC} = \left[\sum_{j=1}^{n_{EC}}\sum_{i=1}^{n} MC_{i_j} + \sum_{j=1}^{n_{EC}}\sum_{i=1}^{n} OC_{i_j}\right] + \sum_{j=1}^{n_{EC}} C_{i_j}} \qquad \textit{Equation 8}$$

Where: n determines the value of cost whether it is due to any breakdown or maintenance or salvage value of an equipment. By contrast, n_{EC} shows the usage value of available several capacities based electrical chillers while $COST_{EC}$ shows total of n types of costs.

2.2. Budget estimation for Thermal Energy System

For cost estimation, the following equation 9 has been employed.

$$\boldsymbol{COST_{TES_1} = \left[\sum_{i=1}^{n} MC_{i_1} + \sum_{i=1}^{n} OC_{i_1}\right] + C_{I_1}} \qquad \textit{Equation 9}$$

Where, Operational cost= OC, Maintenance Cost= MC and $Cost_{TES_1}$ shows initial charges.
To calculate the cost of multiple thermal energy storage systems, the following equation 10 will be utilized:

$$\boldsymbol{COST_{TES} = \left[\sum_{j=1}^{n_{TES}} \sum_{i=1}^{n} MC_{i_j} + \sum_{j=1}^{n_{TES}} \sum_{i=1}^{n} OC_{i_j}\right] + \sum_{j=1}^{n_{TES}} C_{i_j}} \qquad \textit{Equation 10}$$

Where: n determines the value of cost either it is due to any breakdown or maintenance or salvage value of an equipment. By contrast, n_{TES} shows the usage value of available several capacities based thermal energy storage tanks while $COST_{TES}$ shows total of n types costs.

2.3. Budget totality for TSS

Now, calculating the Thermal Storage System (TSS) cost is straightforward using the following equation (i.e., Eq: 11).

$$\boldsymbol{LLC_{TSS} = \sum_{j=1}^{n_{TES}} C_{i_j} + \sum_{j=1}^{n_{EC}} \sum_{i=1}^{n} OC_{i_j} + \sum_{j=1}^{n_{EC}} \sum_{i=1}^{n} MC_1 + \sum_{j=1}^{n_{EC}} C_{i_j}} \qquad \textit{Equation 11}$$

Here, it should be noticed that TES operational cost has been ignored because it is negligible when it has been compared with operating cost of electrical chillers. Hence, it can be said as ES OC is only focused in this research.

2.4. Budget invested for Thermal energy system.

The Capital Expenditure (CAPEX) is allocated across the upcoming time durations, on a yearly basis, which can be calculated using Eq. 12. Once absorbed annually, profit calculations come into play. When the profit turns positive and surpasses the zero line, it indicates that the economic life of the equipment has been reached. This signifies the minimum duration after which the system begins generating profit and successfully recovers the amount of Capital Expenditures.

$$\boldsymbol{Aw = \left[\frac{1}{(1+i)^N - 1 \big/ (1+i)^N \times i}\right] \times P.w} \qquad \textit{Equation 12}$$

3. RESULTS AND DISCUSSIONS

The average production of the plant is 325 RTH per hour, as shown in Table 3.1 for both cases, while Table 3.2 illustrates the average electricity usage by the Thermal Storage System (TSS) at the Gas District Cooling (GDC) plant in academic institute. To produce a single RTH, 0.8 kWh of cooled water is required, equivalent to 0.8 kWh/RTh. This value is multiplied by TNB, Malaysia, to calculate rates in industrial values. Therefore, the rates for off-peak and peak hours are 0.173 and 0.288 RM/kWh, respectively. Assumptions have been made for both cases: in Case 1 (16-hour shift), the initial and last few hours are considered off-peak, while the mid-hours are considered peak hours. In Case 2 (24-hour shift), the initial 12 hours are considered peak hours, and the remaining 12 hours are considered off-peak. Yearly consumption rates are considered for this research study (model). Table 3.3 determines the labor cost related with two cases. By Multiplying with 12months, we convert salary outlay into year. It is multiplied with 2.2, according to the policies of GDC plant for a perk and allowances. Table 3.4 determines the initial cost, which has been invested on installation and procurement of electrical chillers and thermal energy storage system called as capital expenditures (CAPEX).

Table 3.1: Electrical chillers average production at plant GDC

Thermal Storage System	Production Per day (RTh/day) Case 1	production Per day (RTh/day) Case 2
Totality	15600	23400

Table 3.2: Electrical chillers average production at plant GDC

Thermal Storage System	Utilization Per day (kWh/day) Case 1	Utilization Per day (kWh/day) Case 2
Totality	2787	4315

Table 3.3: Electrical chillers average production at plant GDC

Labor	Salary (RM/month) Case 1	Salary (RM/month) Case 2	Sectors	Totality (value in RM)
Engineer	7320	16104	service (Monthly)	257786
			Service (Yearly)	174101.8
Technician	3660	8052	cleaning of Tubes	101260
			Cleaning of Chemicals	9357.4
Totality	10,980	24156		

Table 3.4. Amount of capital invested for installation along with procurement for ECs and TES

Capital Exp.	Basic Investment
Thermal Energy System (10000 RTh)	9000000
Electrical Chillers (three)	3300000

The economic life analysis approach used for the earlier mentioned case is employed to ascertain the project duration at which it intersects the non-profit line and where the amount of capital expenditures (CAPEX) will be recovered. Figure 5.1 illustrates the analysis of the standard case. Economic life analysis is depicted in Figure 5.2 for the case, indicating that the economic life of the described case is attained in the fourth year of operation. It is worth noting that an additional charge for overhaul is required in the seventh year.

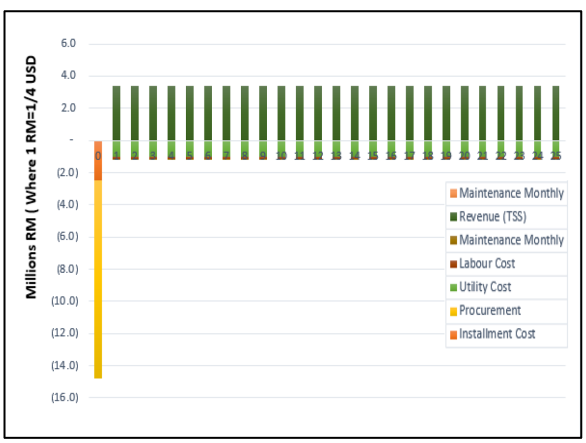

Figure 3.1: Profitability Chart for Case 1 with an 8-hour Double Shift (Constant Estimate)

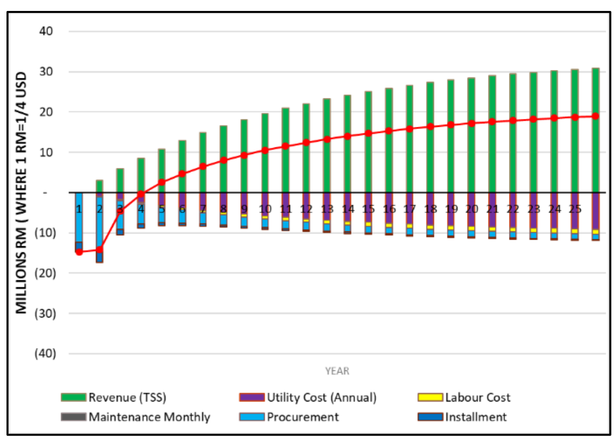

Figure 3.2: Economic Life Analysis for Case 1 with an 8-hour Double Shift (Constant Estimate)

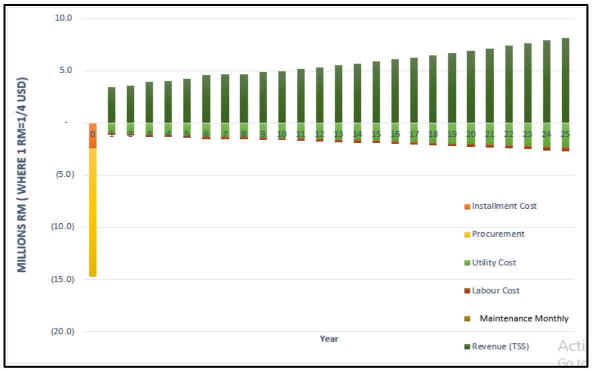

Figure 3.3: Profitability Chart for Case 1 with an 8-hour Double Shift (Influential Values)

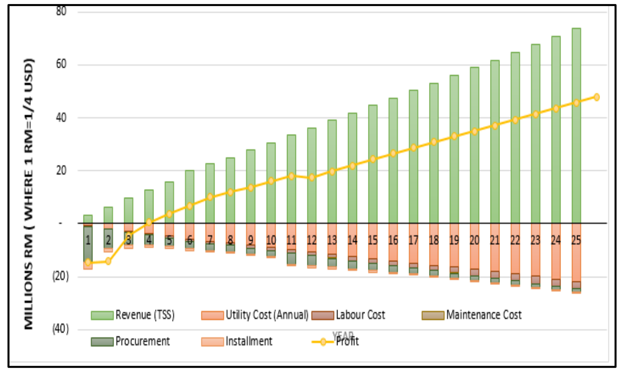

Figure 3.4: Economic Life Analysis for Case 1 with an 8-hour Double Shift (Influential Values)

4. CONCLUSION

The uncertainties associated with randomness and fluctuations in daily life are incorporated into the Life Cycle Cost (LLC) model, achieving the initial goal of the project. The LLC model is employed to assess the efficiency of the Thermal Storage System (TSS), consisting of several thermal energy storage tanks and electrical chillers, located at academic institute, Malaysia. The findings and future suggestions of this research are as follows:

- With or without the dynamic approach in breakeven analysis, indicates that the breakeven point is achieved in the fourth year after the operational procedure.
- Salvage values of equipment and public holidays, as defined by the Malaysian government, are not considered in this research. Therefore, future researchers can employ a probabilistic LLC approach using Monte-Carlo simulation.
- Further research opportunities exist for investigating salvage costs and replacement amounts for thermal energy storage tanks and electrical chillers when these components reach their maximum lifetime.
- The impact of increased fuel prices and inflation rates can be explored to create a more realistic case scenario for future research.

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