Optimal energy management of Ice thermal energy storage-based air conditioning system for commercial buildings in real-time – A review based on POET framework

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Abstract. This paper applied the POET framework to analyze and identify possible energy efficiency activities that may reduce energy costs in HVAC cooling systems with Ice Thermal Energy Storage (ITES) in order to achieve maximum potential cost-savings, particularly for cooling loads in commercial buildings. Significant cost savings may be realized by the optimal shifting of the energy usage profile to the least costly regions of the Time-of-Use (TOU) using the ITES system. Moreover, a further reduction of energy costs may be achieved by introducing renewable energy (RE) sourced systems. A potential reduction of approximately 50% in energy cost savings could be achieved with the application of the POET framework. Improvement in operational efficiency may be achieved if systems were optimally sized and controlled. Studies conducted on control methods have shown that Model Predictive Control (MPC) offers significant benefits of achieving reasonable operational efficiency compared to other methods, particularly on HVAC systems. Combined ITES and hybrid energy systems allow an additional advantage in demand-side management, per the TOU tariff and peak demand. This may ultimately result in minimal energy usage during the costly regions of the TOU tariff, which would minimize energy costs and technology and equipment efficiency may be improved.

1. Introduction

Universally, it is essentially required to sustain and manage the escalating demand for energy [1]. Moreover, the study of green renewable technologies for energy generation and incorporating energy-efficiency schemes to manage energy systems provides reliable solutions to these demand challenges [2,3].

Commercial buildings contribute to the large usage proportion of electricity in the commercial sector, particularly due to the aspect of the building’s heating, ventilation and air-conditioning (HVAC) systems for vast purposes. According to Electricity Supply Industry (ESI)-Africa, the HVAC system consumes a high proportion of the overall energy cost per building, which ranges from 30% to 60% [4]. In retrospect, a government office building with less working hours, HVAC energy cost to overall building energy cost is about 30% while the hotels consume over 50% (Eskom.co.za, 2017), hence commercial buildings consume approximately 40% of the overall energy [5,6].

In view of the progress made with HVAC systems energy efficiency improvement, an earlier study in early 2000 results proved that more than 50% electricity cost is due to cooling and approximately, of 5% of total energy consumption was saved, with Ice Thermal Energy Storage (ITES) implemented in
the HVAC systems [7]. A decade later, an acceptable level of thermal comfort was also achieved in the commercial buildings, in addition to energy savings of up to 30% for the buildings’ energy consumption, using the ITES system by employing proper control and operation strategies [8]. Saving is achievable by understanding the concept of Demand Side Management (DSM) for the applications [29].

Nevertheless, proper implementation proved that the application of a Model Predictive Control (MPC) as a control solution is efficient for ITES systems control [10]. Evidently, research efforts on real-time optimal control of the ITES system have shown huge success [11,12].

In this paper, the POET framework is used to review, analyze and investigate the energy efficiency in the commercial building cooling system. An analysis of the outcomes from the conceptual to future development will be examined. Analysis of data to realize potentials for optimally controlled ITES system in a South African commercial building will be presented.

2. Energy management framework application and implementation

POET framework was adopted for various cases from energy audits in building to energy processes management with a success of reasonable outcomes. Among others, the framework was implemented for mineral processing, pumping system and cooling systems realize an average electrical energy saving of about 40% [13,14,15]. The improvement guidelines may involve the conceptual, active, technical and engineering levels. These levels may each be categorized to represent the Performance efficiency, Operation efficiency, Equipment efficiency and Technological efficiency of the cooling system in the commercial building [16].

2.1. Conceptual level

The conceptual level is a level characterized by identifying the activities to save cost, which requires a low-level skill and therefore involves less expertise. It is mostly characterized by managing the energy in terms of the component analysis and the data for consumption of utility. The analysis of the ITES is based on identifying the component of HVAC’s ITES cooling system, the consumption data and simple activities to save cost.

2.1.1. Technology efficiency at the conceptual level. The electricity consumption of some commercial buildings is shown in figure 1. Comparatively, typical energy consumption in hotels [17,18], hospital [19], office buildings [19], malls [20,21], and University laboratory [22] was compared. It was found that energy consumption for HVAC is relatively high and demands attention, although, varies with the climate and region of usage [23].

2.1.2. Equipment Efficiency at the conceptual level. Here, improvement activities may involve replacement, maintenance of the HVAC systems. However, it is essential to identify the major components of the HVAC system as shown in figure 2 in which each component serves certain purposes [24]. The Air Handling Unit (AHU) is used to re-condition and circulate air while the ice tank storage stores the cooling energy that is charged by the chillers [25]. Baltimore Aircoil avail a video that described the energy consumption and saving from peak utility demand of ITES [26].

![Figure 1. Typical energy usage distribution for some commercial buildings [17-23]]
2.1.3. **Operation Efficiency at the conceptual level.** A simple activity such as switching off the system when not in use, adjusting the operating temperature, setting a timer on the remote control/control reducing infiltration by closing of door or mediums that allow the influx of ambient air to the cooled spaced will contribute immensely to the cost saving of energy bills in the building. The following activities are done at to improve the system: Cleaning [27], purging [28], removal of clogs and sediments [29], monitoring refrigerant level [30], part replacement [31], system replacement/upgrades [32], and, add-on components [33].

2.1.4. **Performance Efficiency at the conceptual level.** At this level, it necessary to secure the technology by assessing proving back up to avoid unwanted failure. However, it is also compulsory to quantify the savings and benefits realized from adopting these concepts. In some cases, a negative effect may cause more failure in the future and if proper performance checks are in place, the unnecessary losses will be avoided.

2.2. **Active level**

Concerning the HVAC ITES systems, it involves the validation of collected data form the initial conceptual level and additional methods or strategies for confirmation of possibilities to improve the energy efficiency and saving for the current HVAC related systems. Active level management may require initiatives to test technologies such as VSD and VRF. Currently, validations are done by implementing the use of equipment, software, and online monitors. Optimal management of the ITES at the current state requires more accurate measures beyond the active level for the improvisation of the energy efficiency of the ITES [34].

2.2.1. **Technology Efficiency at an active level.** HVAC technologies in trend to improve cost and efficiency [94]. The following technologies may be adopted; smart controls, variable speed controls, Variable Refrigerant Flow (VRF) Systems, fuel cell, and ITES [35,36]

2.2.2 **Equipment efficiency at the active level.** At this level, we will consider the equipment associated with the installation of sensors and controllers to improve the efficiency of HVAC systems in the building [37]. The sensors come in different types depending on the application to the HVAC systems. Currently, the sensors have features such as affordability, ease of installation, accurate performance, and reliability. Sensors come in different types such as CO2 sensors, dew point sensors, temperature sensors, pressure sensors, current sensors, enthalpy sensors, economizer sensor, humidity sensors, and occupancy sensors [37].

2.2.3 **Operational efficiency at active levels.** This may involve the use of computer programming with software and training of relevant staff to efficiently operate the programs with regards to conditional variation in factors affecting the building’s cooling requirements.

In the current market, there are software such as ASCENT COMPASS™, Niagara 4, to serve as a workstation to monitor energy management such as efficient equipment starts times, load optimization as well as energy use track optimization for tracking savings [38].

2.2.4 **Performance efficiency at active levels.** It is essential to consider the fact that the technology adopted for energy saving may fail and proper security plans should be available to avoid excessive damages and losses. Firstly, the outcomes from the adoption of the technologies should be provided in a database and be investigated. For instance, South Africa is currently experiencing load shedding in all sectors which demand reliable and effective backup plans. The backup plan may involve the switching of the energy source of the system without causing further loses and damages.

2.3 **Technical level:**

At this level, further energy improvement beyond the conceptual and active level will be considered. For effectiveness, the technology will be narrowed to the ITES technology and combination with RE for cooling purposes. Implementation of initiative and verification of the claimed energy savings from
the previous level may include further retrofitting, automation control, and other strategies to improve the ITES system’s EE.

2.3.1 Technology efficiency at the technical level. Comodo et al. [39] highlighted the importance of weighing the pros and cons of each technology for improving the cooling load efficiency of HVAC systems by qualitative analysis of various cooling systems, to select a suitable option for an energy storage system. However, the establishment of an energy dashboard to compare the baseline technology to that of actual technology. This study will take the baseline as the conventional HVAC system and the actual as the optimized HVAC system that incorporates the ITES and the renewable energy system. This will purposefully help with the tracking of the worth of the technological initiatives of ITES and hybrid systems. Mostly, the utilization of ITES and RE may require extra capital cost, though, this may be recovered in the future at a reasonable payback period [40].

2.3.2 Equipment efficiency at a technical level. ITES system has been proven feasible, in which certain conditions are required to achieve the intended energy cost savings. The conditions include a match between control strategies in relation with DSM and electricity tariff structures, which simultaneously influences the ice storage rate and electric price ratio, in relation to system economy, for various types of commercial buildings [41]. Hybrid energy systems may assist by supplementing energy supply in order to avoid the total reliance of the energy supply on the grid only, particularly during peak periods; hence, increased options of cleaner energy sources and efficiency improvisation. For instance, the utilization of DC ice making, Bi-directional inverter on a PV/T are some of the options available. Considering the cooling profile for the day, there is a match between PV or PV/T profile and the cooling needed during the day, which makes the PV/T a suitable candidate for a hybrid energy system [42,43,44,52].

2.3.3 Operation efficiency at the technical level. The operational efficiency can be improved using desktop models that aim to meet the energy requirements of a building. Software tools are usually designed to manage energy consumption relative to time and occupants’ demand [45]. However, the limitation of the ITES exists when there are flat tariffs and may lead to excess cost if applied to them wrongly. In some cases, the use of ITES experienced failure due to negligence in identifying the feasibility of the ITES system [46].

2.3.4 Performance efficiency at the technical level. Pointers such as cost, production, sources, and environmental effect are analyzed to identify/validate/evaluate energy efficiency improvement opportunities. After the selection of model and verification, the commissioning of HVAC-systems in office buildings showed a reasonable saving when compared to the baseline system [47].

2.4. Engineering level and prospective improvement

The engineering level should be focused and involve research work and analysis that will result in an innovative and accurate contribution to the current technology. At this point, the energy-savings and efficiency will focus not on all the concepts but that of the ITES and RE of the air-conditioning system. The engineering level management usually involves a higher initiative that results in longer payback years and higher percentage saving of total energy consumption.

2.4.1 Technological efficiency at the engineering level. Adopting the ITES on the HVAC system may only save energy and other factors such as system efficiency, COP, total energy consumption still need attention to increase the reliability of ITES technology. The inclusion of various options of RE and upgrade of the ITES and HVAC system to a level above technical level may be identified. The inclusion of RE technology and real-time optimization is an option to improve the system and resolve previous challenges. The RE may not only be PV or PV/T with DC ice maker as described in figure 4, but it could also adopt vapour absorption refrigeration [42].
2.4.2 Equipment efficiency at the engineering level. At the engineering level, security and maintenance plans should be analyzed rather than recording them on a dashboard. For example, a technology with an automated trouble-shooter and a maintenance tool can be programmed on the equipment. Regarding the technological efficiency, advanced building automation systems can be investigated to optimally and dynamically change the air-conditioning temperature setpoint according to real-time weather conditions and occupancy level, energy rate, and energy consumption saving objectives, amongst others.

![Proposed HVAC cooling system with ITES and RE](image)

2.4.3 Operation efficiency at the engineering level. Improvements are possible by applying advanced energy system optimization skills. As a measure, the operation timetable of an HVAC system can be optimized by incorporating the maintenance schedule, occupancy level, ambient temperature and moisture of the building. A load shifting plan integrated to real-time forecasting and TOU for the cooling load profiles on the ITES can be made. A reference is a study that illustrated the possibilities of implementing control techniques (On-Off Control, PID, Robust Control, Adaptive Control and, Intelligent Control) done by simulation examples in the analysis of control performance and energy consumption [48,49].

2.4.4 Performance efficiency at the engineering level. In this area, the information provided in the existing energy console can be further expanded. All the major performance efficiency indicators such as energy cost, energy waste, carbon emission, staff knowledge, and skill level, life cycle cost, and return of interest, amongst others, can be added in the console. Real-time optimization was used to achieve over 50% energy cost savings without compromising thermal comfort by weighing factors such as CO₂ effects, temperature, pressure, humidity and occupancy as variables [50]. The challenges at the advanced level are inaccuracy and slowness simulation speed which can be resolved by application of high computing technologies and advance modelling and simulation techniques [50].

3. Key findings on reviewed literature

With all the merits and applications of the ITES, there are currently challenges in utilizing the technology at its best. Moreover, there is a lower COP when compared to a conventional chiller system. The cost-effectiveness of the ITES is thus justified only when the electricity consumption is charged under TOU tariff and efficiently optimized. It is evident that most studies previously in optimal control, particularly in real-time, involve the HVAC system without the ITES. Furthermore, there are still problems and challenges faced by the usage of ITES, particularly with the non-optimal operation of the system with considerations to the cost savings and energy efficiency applicable to demand-side management. However, from investigations conducted, it revealed the current lack in the new technological application of a control methods strategy that involves the real-time application of Fuzzy
logic, Neural network, and MPC. Literature also revealed the MPC outperforms all other methods of control in terms of performance. It is recommended to simulate in real-time optimization to avoid software errors.

Moreover, due to the increase in overall energy production drawn by the ITES to the HVAC system, the hybrid systems of other renewable energy. Furthermore, the optimal control methods applied to these hybrid systems with regards to operation in terms of the TOU tariff lacks exploration. Considering the hybrid system, the solar PV or PV/T system can be used here to produce energy that will be used in the peak and matching day periods for cooling load profiles such as those of shopping centres, hotels and hospitals. In conclusion, as PV/T production is matching the commercial cooling demand, it motivates the inclusion and further investigation of PV/T in the ITES and HVAC system [43]. However, the entire system, including the PV/T, needs to be optimally designed and controlled. In view of the POET framework at each level, the potential estimated cumulative efficiency and percentage energy cost savings are plotted for a typical building HVAC system in figure 3. The ranking is from the outcomes of qualitative decisions on the overview of literature and investigations done and corresponds with Xia’s initiative [16].

Based on reflection, it is worth the effort in improving the HVAC system at the engineering level. In conclusion, a higher percentage of improving may be achieved in the long run. Regarding a study on a commercial building in South Africa, and analyzing data, by comparison, the building with conventional controlled and optimal controlled Chiller power inputs, power output monthly data for a year at the same cooling load, some findings are derived [51]. Figure 4 shows that the optimally control chiller still with reasonable performance, however, if the system is managed at the engineering level, the output would have been exceptional [51]. In Figure 5, the COP was reasonable after optimization as the yearly average for the conventional system was 2.2, while that of the optimal was 3.07. This indicates that an optimally controlled system may improve the COP for the chillers. Figure 6 revealed how much energy cost savings could be realized from the optimally controlled system. Furthermore, the energy cost went down from R 41 159.70 to R31 086, hence with a savings of R10 073.70 after the optimally controlling of the system.
4. Conclusion
The energy usage in the commercial buildings among other sector is high in enough and require some attention. The annual average electricity in cents per kilowatt per hour has increased tremendously in the past decade (2008 to 2018) in the commercial sector from 31.61c/kWh to 111.25c/kWh. HVAC systems in the commercial buildings contributed to the increase in the demand for electricity with up to 60% portion of the building’s overall energy cost. It is worth giving attention to activities that could improve energy efficiency and save costs to reduces the current energy crisis.

A POET framework at various allowed a structured and thorough guideline for energy management to evaluate the energy-saving and efficiency improvement potentials.

A case study of a commercial building also revealed the potential saving that could be realized from the adoption of optimal control strategies of ITES systems in HVAC for air-conditioning.

5. Recommendations for future work
With the potential revealed in the study, ITES will be considered for further improvement which may involve;

- The use of on-site historical cooling to confirm the results from optimally control ITES systems.
- Mathematical models for real-time optimal control of the hybrid energy system (PV and grid) connected to HVAC and ITES. To achieve this, a model of each isolated system (that is, the HVAC, ITES and PV) will precede the combined system as shown in the figure 2. Isolating the set-up will allow a baseline comparison with the proposed system.
- Suitability of different control strategies that include both open-loop and close-loop strategies such as MPC will be considered under various conditions. Hence, further recommendations will be provided.
- Techno-Economic Analysis of the proposed optimally controlled system compared to the baseline system (existing system without ITES and PV system).
- A life cycle cost analysis of the proposed system to analyze its feasibility.
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