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BUILDING ENERGY SYSTEMS OPERATION OPTIMIZATION WITH ICE STORAGE – A REAL TIME APPROACH

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Abstract

Energy consumption in BESIS is in close relationship with the operation logic of the associated HVAC. Furthermore, engineering calculation norms describe design conditions as the best operating mode for ISAC. Since the performance of ISAC sub-systems are susceptible to environmental variations and operation priorities, controller based dynamic operation optimization of ISAC sub-systems is desirable from both sustainability and business perspectives. This results in an increment in the corresponding heat transfer rate and ultimately, an improvement in the overall efficiency of the BESIS.

In this article the assessment results of the dynamic behavior of BESIS in a typical building under certain optimization strategies is presented. Then BEMWIS has been fitted to BESIS to analyze daily operational data of the energy system, to balance load via stored ice latent heat, and to properly respond to the variable inputs. The knowledge based control system uses equipment operation data and energy consumption, developed in form of data bases and mathematical models. The optimization methodology has been developed based of empirical information from the running ISAC. The optimizer methodology predicts load as the result of *the decision maker system calculations, and then records, shifts, and eliminates unnecessary energy consumption.*

Keywords

Ice storage energy systems, HVAC, BEMWIS, BEMS, Energy management systems, CAPEX, OPEX, Control systems, Optimization, Partial load, Full load, Latent heat

1. Introduction

The application of ice storage in BEMS has become so commonplace that they are simply referred to as standard means of consumption management facilities. However, the dependency of building energy systems on environmental conditions is so high that the combination of both systems can consolidate greater level of energy savings. Therefore, BEMWIS has potentials to control energy consumption and peak shaving in building mechanical and electrical systems simultaneously. According to the information obtained from an assessment carried out on the energy consumption of non-residential buildings over a five-month period (Carlson, Leach, & Johnson, 2015), less than 20% of buildings fitted with central heating and cooling systems had BEMWIS control systems. Also more than 30% of the larger buildings have been equipped with such management systems. ASHRAE standard series 90/1P introduces the specifications of BEMS (ASHRAE Standard, 2013). The flexibility and reliability of energy management systems has raised interests towards the application of BEMS to adapt with the nature of building energy systems and associated variable boundary conditions (Robyns & Soltan, 2016).

To assess the advantages of applying the combined technology, the understanding of BEMWIS capabilities is essential. BEMWIS is well known for its capability in increasing comfort, efficiency of buildings, and peak time load shaving or shifting. Input data from sensors are collected throughout the building in large BEMWIS. Then proper signals based on control strategies and peak hours load estimation are sent to a diversity of actuators in the building and BESIS. Information data such as peak hours load prediction, inlet air temperature, interior air temperature, and hot/cold water temperatures are measured and recorded. In addition, equipment performance and energy efficiency are calculated for further actions.

The followings are among the benefits of using BEMWIS in buildings:

- In addition to OPEX, BEMWIS technology reduces CAPEX due to the size of mechanical and electrical equipment. This in turn leads to an increment in the degree of comfort and greater flexibility during the operation of associated equipment.

- The addition of BESIS concept to conventional BEMS would result in substantial energy saving due to cooling load shift to off-peak periods.
- In countries or regions with well-developed electricity tariff systems, a great cut-off costs would be applicable due to the flexible nature of BEMWIS.
- Building operators would access to real time information from the working conditions of the building energy systems to the load shifting. Therefore they would be able to monitor effectively the energy system for unpredictable issues and corresponding performance variations.
- From the applicability point of view, BEMWIS gives the ability to control demand, shave load, shift load, and reform heat load according to the application type.

This paper examines the results of applying BEMWIS with more advanced energy management concepts to the 8000 m^2 research center building, which has already been assessed via the application of BEMS (Robyns & Soltan, 2016). It has been investigated that the addition of BESIS to the former energy management strategies (Robyns & Soltan, 2016) results in greater energy savings. Here, semantics for BEMWIS includes advanced energy management strategies, load leveling algorithms, and load shifting procedures to off-peak hours. The system analyzes daily power consumption patterns as well as peak hours' load, and then either shifts or shaves unnecessary energy usage. The uniqueness of this research results from the application of advanced optimization methodologies to determine control strategies in medium to large scale real-time systems.

2. Systems description

Figure (1) shows a schema of the under study building HVAC system and BESIS facilities. According to the figure, the HVAC system comprised a mixed type of fan coils and air handling units. Air-handling section of the HVAC system supplies conditioned air for laboratories, conference halls and corridors, whereas fan coils are mainly used for heating and cooling of the office rooms. The building energy system includes five chillers with nominal capacity of 150 tons of refrigeration each, and wet type cooling towers. Additionally, the required heating for colder seasons is supplied with three boilers, each with a nominal capacity of 1000000 $(kCal/hr)$. Figure (1) does not indicate reserved capacities.

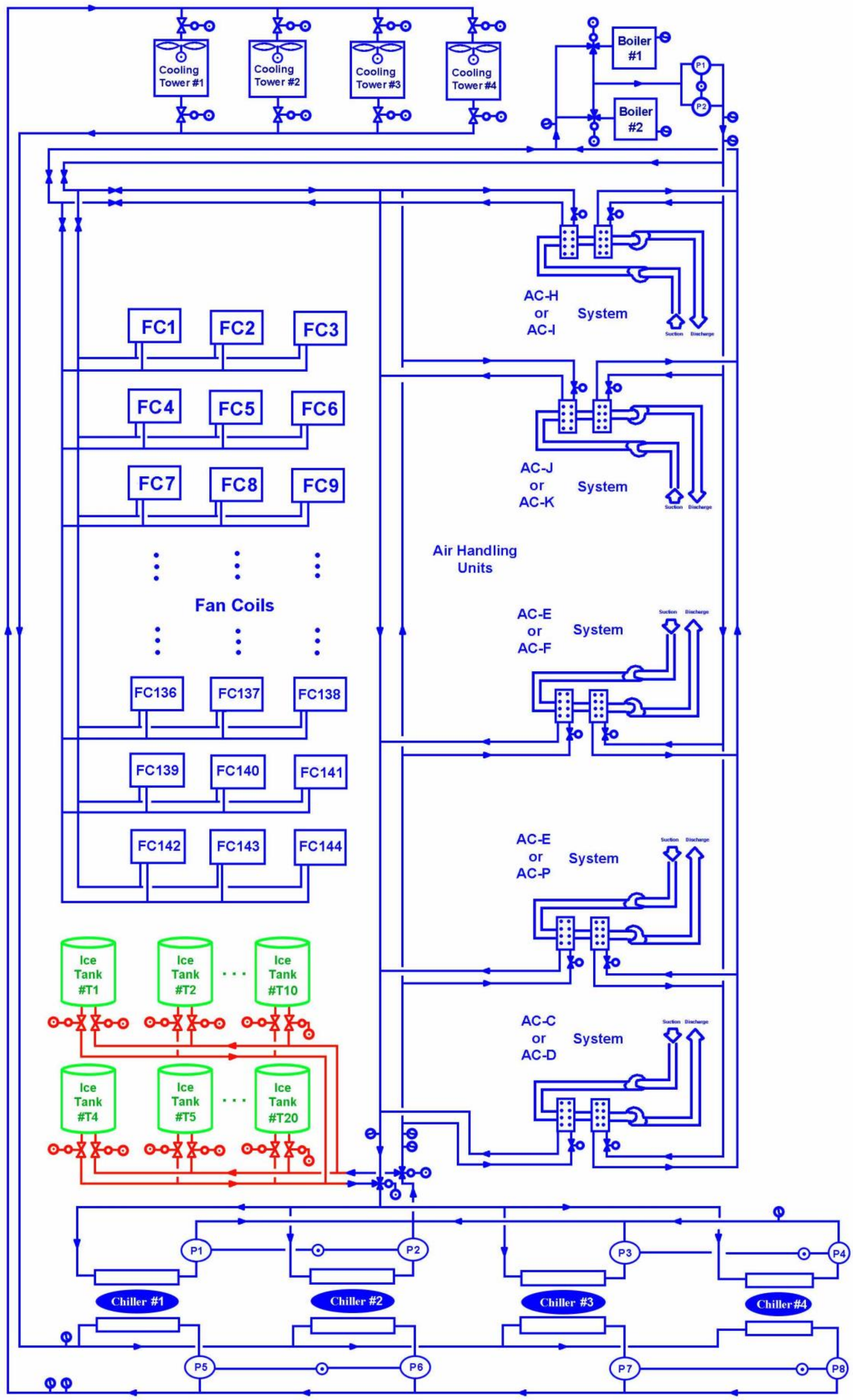


Figure 1: *Schematic of the building HVAC system*

The BESIS has been designed with 20 ice tanks with average discharging rate of 20 ton over 8 hour for each (Figure 2).

Figure 2: *Ice storage tanks*

3. Consumption Management Potentials

Since the CAPEX and OPEX of the central cooling plant is of crucial importance for this research, all efforts were to either reduce the power consumption of the energy system components and shift or level cooling load where and when possible. Measurements have shown that chillers, condensers, pumps, fan coils and air handlers are the main energy consumers in the HVAC system, and that chillers with total power consumption of 689.2 kW, are the major users in the ranking. The coefficient of performance for chillers is calculated according to the following equation:

$$\frac{1}{COP} = -1 + \frac{T_c^{in}}{T_e^{out}} + \frac{-A_0 + A_1 T_c^{in} - A_2 \frac{T_c^{in}}{T_e^{out}}}{Q_e} \quad (1)$$

According to the equation (1), COP maximizes when chiller works under full load. Furthermore, according to equation (1), COP increases with Q_e at constant temperatures. In conventional HVAC design methods (as was considered during the BEMS development), cooling load is evenly shared among parallel chillers (Figure 3).

Figure 3: *BESIS chillers with parallel configuration*

BEMWIS not only balances cooling load distribution based on maximum load assignment to individual chillers, but also considers load shifting from peak time (here 19:00 to 23:00 pm) to off-peak hours. This would guarantee the achievement to the maximum COP.

Water pumps are generally single speed, which means that the associated electricity consumption is almost constant, even though, it is subject to the variable tariffs. However, according to the same design methodology pumps are normally considered in parallel configuration (Figure 4).

Figure 4: *BEMWIS pumps with parallel configuration*

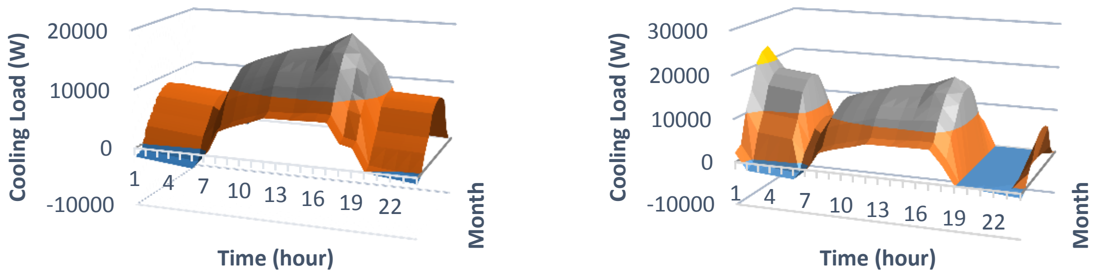
This would provide more flexibility in water flow rates which is applicable via addition of flow control instruments (Figure 5) through using a PLC based energy management system (Figure 6).

Figure 5: *Flow control instruments*

Figure 6: *PLC based energy management system*

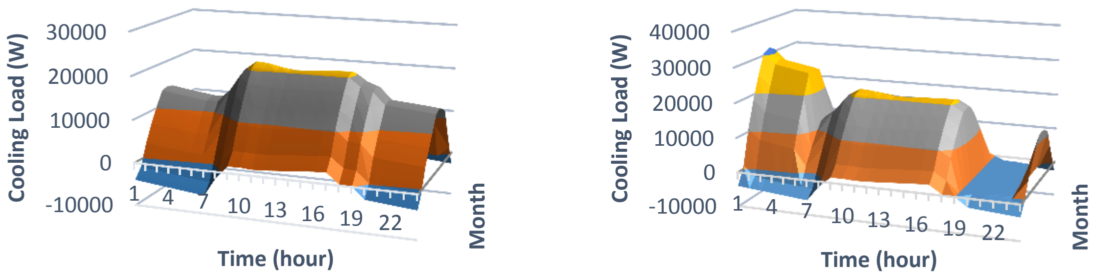
The electrical power needed for air movement is consumed in both air handling units and fan coils.

Building heat load distribution has specifically been focused in this study. All commercially well-known HVAC software which represent load calculations, consider maximum heat load as a part of design methodology. In the current research the combined effect of variable heat loads, and also peak time heat load in different sections of the building have been studied simultaneously. Time dependent heat loads are caused by variable environmental inputs such as radiation and ambient temperature. Moreover, electricity tariff at peak times are mainly substantial. Therefore, the cooling and heating loads of the energy system, as well as load shifting and/or load leveling, have been defined as time dependent phenomena for the decision making system. It is also noteworthy in this research that not only cooling loads are considered as time dependent, but also they vary in different sections (zones) of the building. Figures (7a) to (9a) show three-dimensional load distributions in some of the building zones. Furthermore, figures (7b) to (9b) represent interpreted load distributions of the same zones by the BEMWIS for the chillers which convey load shifting or shaving. The diagrams represent hourly heat loads in terms of the day of year. Apparently, heat load variation in different sections of the building is substantial.



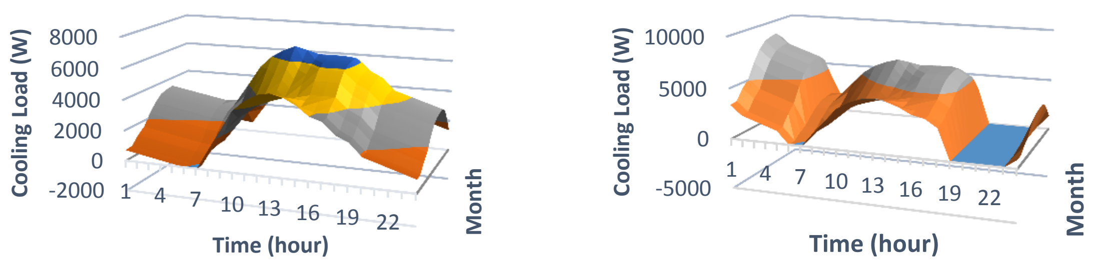
(a): *Actual heat load* **(b):** *Interpreted heat load for chillers by BEMWIS*

Figure 7: *Yearly load distribution in zone 1*



(a): *Actual heat load* **(b):** *Interpreted heat load for chillers by BEMWIS*

Figure 8: *Yearly heat distribution in zone 2*



(a): *Actual heat load* **(b):** *Interpreted heat load for chillers by BEMWIS*

Figure 9: *Yearly heat distribution in zone 19*

4. Optimization Strategy

Optimum control in current project is exerted via adherence to advanced optimization strategies. The optimization strategies for the BEMWIS comprise the following assumptions:

- BEMWIS analyses cooling requirement to determine whether it is caused by the environmental variations or initiated based on the peak period demand. Accordingly, BEMWIS decides to apply zonal mode to balance cooling load in the building zones, to recharge latent heat in the thermal storage system and associated BESIS tanks, or to apply a proportional combination of both strategies.
- BEMWIS optimizes the operation of individual components. The overall performance of the energy system becomes optimum when the individual components performances are optimum.
- Chillers would also work during off-peak hours to store enough ice either for load shifting or load shaving from peak hours. Load assignment to a chiller commences when previous operating chillers are under full load. In traditional HVAC, load distribution occurs evenly among operating chillers.
- Cold water is distributed among zones according to cooling requirements. Then proportional flow switching will be in place based on cooling load demand.
- The number of operating pumps is proportional to the cold water flow rate requirements.
- The number of operating fan coils in each zone is proportional to the heat load.
- The number of operating condensers correlates to chillers on/off mode situation.

With the addition of thermal storage concept to the dynamic control logic, CAPEX will diminish by means of decreased cooling capacity requirement of the building energy system. In some cases chiller size have even reduced up to 50% of the peak load. While working under thermal storage mode, the storage system discharges when the building load is greater than the chiller output, whereas it is charged when chiller output excels the building load;

Load shifting is aimed to shift heat load fully or partially from peak time to off-peak hours. Even though the CAPEX increases limitedly due to the capital cost of storage tanks and associated sub-systems, the energy system takes advantage of not only lower off-peak energy prices, but also OPEX costs while diminishing or eliminating the chiller on-peak operation.

5. Problem Optimization

When the building energy system operates in optimum mode, heat and mass transfer are in steady state at all times. In this situation the BEMWIS monitors mutual effects of different components on each other, and records on-peak and off-peak hour loads. On this basis, hourly load in different zones have been calculated using mathematical models. As can be seen in figures (7) to (9), the obtained results from the models are intrinsically non-linear due to the non-linear nature of heat transfer. The results of solving a system of a nonlinear multi variable equations are essentially dependent upon the specific nature of the problem nonlinearity. The solution to multivariable optimization problems lies in the represented search methods suggested by scholar researchers (Chen, Prasad, & Jaluria, 2016), (Smyth, 2015). In the current project, the method of optimization of multivariable equations through simplexes has been used to minimize the objective function (Smyth, 2015).

6. Objective function

The amount and intensity of energy consumption correlate with difference between indoor and outdoor temperatures. Then OPEX for the building energy system could be calculated through the following equation:

$$OPEX = C_c + C_{co} + C_p + C_f \tag{2}$$

Where:

1. C_c: Cooling costs in warm seasons
2. C_{co}: Heat removal costs to higher temperature source (ambient air)
3. C_p: Pumping costs to maintain fluid flow
4. C_f: Blowing costs to maintain on-coil air flow

BEMWIS has been programmed to calculate OPEX as a function of time regardless of the system operation during peak hour or off-peak period. As stated before, the reason behind time dependency of the logic is the difference between off-peak and on-peak electricity tariffs which is quite commonplace in most developed countries. Even so, in some part of the world there are more than two tariffs for electricity. Consequently, chillers' operation distinguished by different tariffs not only take advantage of reduced size, but also can generate cooling load at a much lower OPEX. Here it is assumed that all equipment and systems use identical power sources. For example, they are all assumed to be fed with a three-phase electric power.

The first cost is expressed via the cooling supply by chillers, $C\ (kW)$. If $a\ (kW^{-1})$ is consumed power cost, then:

$$C_c)_i = a_0 a_i C_i \tag{3}$$

Where a_0 is the variable seasonal tariff coefficient for electricity and varies between 0 and 1 ($0 < a_0 \leq 1$). The subscript i is the time mode index, with $i = 1$ for off-peak hours and $i = 2$ for on-peak hours.

The second cost correlates with the power consumption in condenser fans. If $C_o\ (kW)$ be the condenser fans power consumption, then:

$$C_{co})_i = a_0 a_i C_{oi} \tag{4}$$

The third cost is proportional to the pumping power. If $P\ (kW)$ be the pumping power, then:

$$C_p)_i = a_0 a_i P_i \tag{5}$$

Finally, the fourth cost is the power requirement to blow air on coils. If $F\ (kW)$ be the blowing power, then:

$$C_f)_i = a_0 a_i F_i \tag{6}$$

The BEMWIS can operate the HVAC system under optimal conditions, if only the proportion of the required cooling in hot months of the year to the total cost is maximum:

$$J_c)_i = \frac{C_i}{(C_c + C_{co} + C_p + C_f)_i} \tag{7}$$

Or:

$$J_c)_i = \frac{1}{a_0 a_i + C_r)_i} \tag{8}$$

Where:

$$C_r)_i = \frac{a_0 a_i (C_{oi} + P_i + F_i)}{C_i} \quad (9)$$

The coefficient a_i is a function of current off-peak and on-peak electric power costs. Optimal geometry plays an important role in the analysis of the objective function. Optimal analysis would also minimize overall costs associated with the problem constraints.

7. Results

Figure (10) shows hourly power consumption for chillers in design day for the examined building with BEMS and BEMWIS in comparison with the traditional building energy systems. According to the chart, the average differences between chiller power requirement with BEMS and BEMWIS, decrease from 26 % and 29% at 7 am to a6% and 18.5% at 3 pm, and then to 4.05 and 6.02% at 6 pm, respectively. Furthermore, the average reduction in chiller power requirement is about 18.7% for BEMS, whereas the corresponding reduction in BEMWIS is 22.9%. The reason behind the chiller COP increment during mid-day is that it operates in full-load in the building with BEMS. Another reason for chiller COP increment is that the reduced size of chillers due to load shifting or load leveling strategies would result in more individual chillers working under full load, which semantically convey their higher performance.

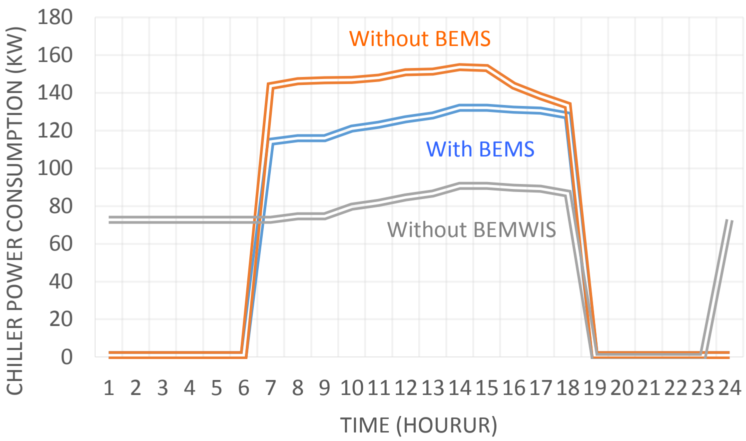


Figure 10: *Chillers power consumption variations in design day in July*

Figure (11) indicates hourly consumption of electrical power in fan coils. During warmer times of the day both BEMS and BEMWIS diminish the number of fan coils in lower heat load zones. At the same time the control system directs cold water flow to higher heat load zones. The results shown in figure (11) indicate that flow diversions which normally happen via control valves have increased the overall efficiency of the HVAC system. According to the chart, the average difference between fan coils power consumption in both systems increase from 7.19% and 9.33% at 7 am to 9% and 12.2% at 3 pm, and then again decrease to 5.5% and 9.5% at 6 pm, respectively.

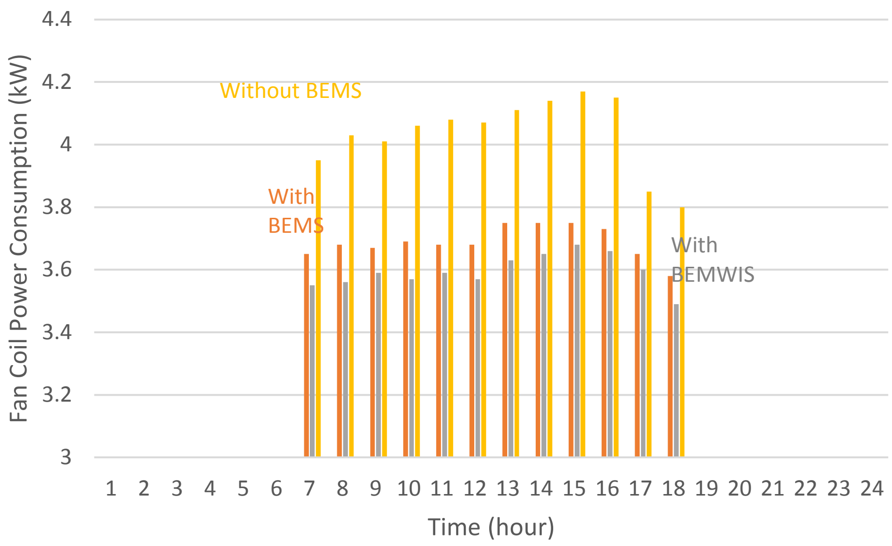


Figure 11: *Blowing fans power consumption variations in design day in July*

Figure (12) compares pumping power requirement in the energy system equipped with the BEMS and the BEMWIS, with pumping power consumption in traditional systems. It is clear from the graph that during the peak period at about 3 pm, the consumed power in pumps for all cases are equal.

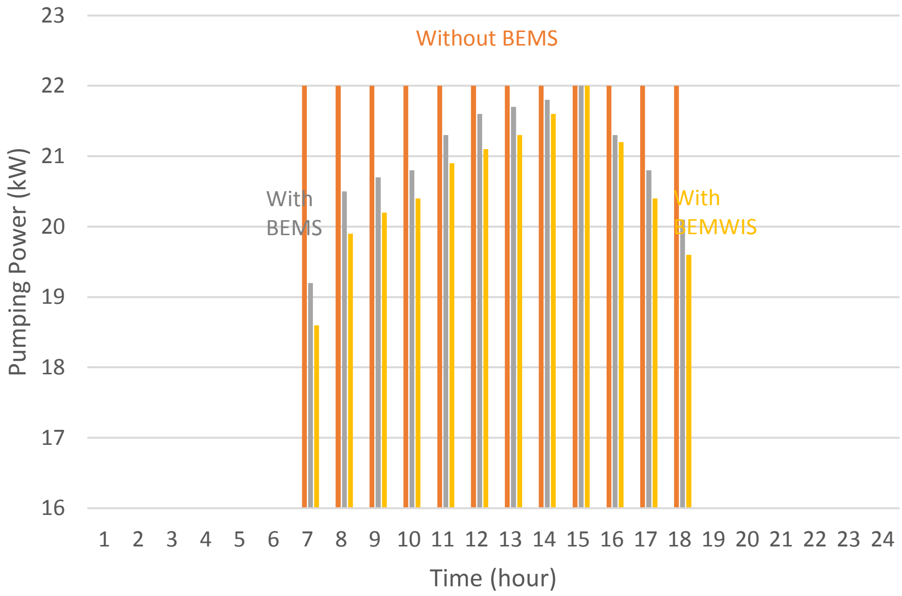


Figure 12: *Pumping power consumption variations in design day in July*

However, during off-peak period, less pumping power is needed due to the operation of the energy system with BEMS, and even lower power is needed for the system with BEMWIS. In this situation, the difference between the required average pumping power in both systems with BEMS and BEMWIS decrease from 9.3% and 13.2% at 7 am to 0% at 3 pm, and then increase to 6.5% and 10.4% at 6 pm respectively, in comparison with the traditional system. In the traditional engine room, pumps used to operate all through the day and were only turned off according to the operator discretion.

8. Conclusion

The obtained results from the project development confirms the existence of substantial energy saving potentials in buildings through the usage of BEMWIS. According to the studies carried out, energy savings by means of BEMWIS promises greater improvement in comparison to conventional methods of reducing energy consumption or even the results obtained through the application of only BEMS in (Robyns & Soltan, 2016). In order to achieve acceptable levels of building energy saving, upgrading BEMS to BEMWIS which hires a combined methodology of dynamic response to building load variations and storing latent heat in BESIS tanks would be essentially recommended. The agreement between obtained results and empirical observations not only fortifies this hypothesis, but calls for further feasible research work based on different scenarios. Obviously, the traditional methods of air conditioning might only provide the minimums.

9. List of Symbols and Abbreviations

OPEX: Operating Expenses

CAPEX: Capital Expenditure

BEMS: Building Energy Management Systems

BEMWIS: Building Energy Management with Ice Storage System

PLC: Programmable Logic Controller

BESIS: Building Energy Systems with Ice Storage

ISAC: Ice Storage Air Conditioning

$A_0 - A_2$: Constant coefficients

COP: Coefficient of Performance

Q_e (J): Chiller cooling load

$T_c^{in}(°C)$: Chiller condenser inlet water temperature

$T_e^{out}(°C)$: Chiller evaporator outlet water temperature

i: Time mode index

a_0: Variable seasonal tariff for electricity

a_1 & a_2 (kW^{-1}): Off-peak and on-peak power consumption cost unit

J_c: Objective Function

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