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Modeling the Sequence of Operation and Time of Partial Load in Vapor Compression-Absorption Hybrid Chiller Plant in Order to Energy Saving

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Abstract: The importance of energy consumption and environmental protection is one of the key issues of the past decade. Most of the energy consumption during the summer season in residential buildings, offices, hospitals, and hotels is related to their chiller plant. The highly variable cooling demand of the buildings connected to a hybrid chiller plant has to be distributed among absorption and vapor compression chillers to achieve higher energy efficiencies. Cooling load sharing strategies in chiller plants have a significant impact on energy consumption and consequently with more productivity and environmentally protected. This paper examines the behavior and pattern of energy consumption in a hybrid chiller plant that includes a combination of vapor compression and absorption chillers. In order to properly understanding the pattern of energy consumption, an existing mechanical room for a hospital in Tehran has been studied for six months and its energy consumption has been compared with the software modeling. This comparison includes the capacity of each chiller, the amount of energy consumed by vapor compression chillers and absorption chillers, and the percentage of their cooling energy allocation. The results indicate that the sequence of the chiller function and how they are placed in the circuit during a partial load is in the highest importance in viewpoint of energy saving.

keywords: Chiller Plant, Energy Consumption, Sequence of Operation and Time of Partial Load

1. Introduction

Absorption chillers can change a building's thermal and electric profile by shifting cooling from an electric load to a thermal load. This shift can be very important for facilities with time-of-day electrical rates, high cooling season rates, and high-demand charges. Some facilities with high-demand charges find it economical to install hybrid chiller plants with both vapor compression and absorption chillers. Building energy managers can take advantage of fuel diversity absorption chillers are used when electric rates and demand charges are high, and vapor compression chillers are used when electric rates and demand charges are low.

One of the centers where the air conditioning system is of great importance is health centers and hospitals. Hospital mechanical rooms are the heart of the building, and disruptions in its proper functioning can lead to irreparable risks such as the spread of viral diseases, severe infections, and even death of patients. Failure to pay adequate attention to the HVAC system can lead to many problems and dangers. For example, if the ventilation system of an operating room with transplant organs patients will have a risk of death and infection. Simultaneous use and commissioning of the heating and cooling system throughout the year is another important issue in the design

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of the air conditioning system of the building. Wards like surgery rooms in the cold seasons also require a cooling system, while parts like the hospitalization of patients in the same seasons require a heating system, while each part has a specific humidity, temperature and pressure according to its usage in accordance with domestic and international standards(Ministry of health and medical Education, 2012; ASHRAE Application Handbook, 2015). According to a report published in the US DCD magazine (DCD, 2013), when a hospital is equipped, the largest construction cost per unit area is related to hospital HVAC facilities and ventilation systems. According to a report by the AEO (EIA, 2012), the energy consumption of buildings in the United States in 2010 is 41% of primary energy consumption. According to information provided by the US-EIA, a significant portion of the energy consumed by the hospital (electricity & gas) is spent on HVAC facilities. According to the International Energy Agency (IEA, 2008), 20 to 40 percent of the final energy in developed countries is related to heating, cooling, and air conditioning systems. In a report presented by Louise Perez Lombard et al (Lombard, Ortiz & Maestre, 2011) heating, cooling, and air conditioning systems have the highest energy consumption of about 50% of the final energy of buildings, and they account for between one third and one-fifth of the final energy in developed countries.

According to studies done by Saldur et al., more than 40 percent of energy consumption in commercial and industrial buildings for cooling is related to energy consumption of chillers (Saidur, Hasanuzzaman, Mahlia, Rahim & Mohammed, 2011). Of course, this amount of energy in the chillers is being optimized. For example, water-cooled chillers in the 1970s had a power consumption of 0.9 kW / ton, which after thirty years passed was reduced to 0.5 kW / ton (Jayamaha, 2008). According to research by Sunder Raj et al. optimizing the performance of chillers in multi-chiller operating systems with a mean capacity of 40% has a 20% reduction result in energy consumption of the plant (Thangavelu, Myat & Khambadkone, 2017).

One of the energy modeling software used to model building shells, as well as the air conditioning and central mechanical room system, is eQuest software. With the modeling of a hotel in China with eQuest software, Jincheng xing et al. calculated the difference in theoretical and practical power consumption by 15% (Xing, Ren & Ling, 2015). Also, according to the measurements, the coefficient of performance in the Vapor compression chillers is less than 4 at part load. Neto Flavio et al. stated that eQuest software is a valuable model for managing BEER proposals (Neto & Fiorelli, 2008). Ming Tsun Kea et al. in modeling the office building by eQuest software, had reported that the mean bias error (MBE) and root mean square error (RMSE) for uncalibrated simulation results are 24.48% and in the calibrated model it was 0.37%, compared to actual energy consumption (Kea, Yeha & Jian, 2013). Sozer modeled residential buildings in eQuest software and he examined the effects of building shells on energy consumption and concluded that optimizing building shells would improve 11.33% of building energy consumption (Sozer, 2010). G. Kim et al. studied the effect of the double low- E windows with a solar film with eQuest software on annual electric energy consumption and peak demand of the commercial building (Kim, Lim, Lim, Schaefer & Kim, 2012). As a result, internal and external solar film coatings reduced cooling loads by 2.2% and 27.5%, respectively.

One of the challenges in designing a central mechanical room for buildings such as hospitals is the type of chillers (Vapor compression or absorption). Due to the presence of a steam system for use in a launderette, disinfection area, etc., it is possible to use absorption chillers by having increased boiler capacity. Also due to the sensitive and variable temperature conditions in hospital spaces, the use of Vapor compression chillers due to its flexibility and less contamination in the hospital is recommended. The purpose of this research is to determine the amount of energy consumption of electricity and natural gas in the correct cycling of both Vapor compression and absorption chillers concerning capacity changes and sequencing. In order to properly understanding the pattern of energy consumption, an existing mechanical room for a hospital in Tehran has been studied for six months and its energy consumption has been compared with the software modeling. Proposing the sequence of operation and time of partial load of chillers in order to save energy in hybrid plants is the novelty of this investigation.

2. Description of Selected Hybrid Chiller Plant

In order to study the energy consumption pattern of a hybrid chiller plant, a separate study was made on the energy consumption of Vapor compression and absorption chillers and their behavior in the mechanical room of the Heart Center Hospital of Tehran. The complex has an area of 18,000 square meters on 8 floors, taking into account the ground floor, and also has 3 floors below ground level. The most important spaces of the hospital which require a HVAC and ventilation system, are in the reception area, radiology and laboratory on the ground floor, operating rooms on the first floor, ICU, CCU in the first and third. The air-conditioner room (32 air-handling units) is located on the second floor and the 3, 4, 5, 6 floors are included in hospital rooms. The 7th floor is for physicians' rooms and dormitories. The restaurant, the chapel, and the CTI Anjou are located in the minus one Floor, kitchen, CSR and laundry room on the minus two Floor, and the mechanical room, lab and parking are located in the minus three. Table 1 obtains the main equipment in the mechanical and air-handling rooms.

There are a total of five chillers for the cooling system in the central mechanical room of the hospital , three of them are a single-effect absorption chiller each with a capacity of 525 tons and two Vapor compression chillers with screw compressors and air-cooled condensers, each with a nominal capacity of 500 tons and 350 of actual ton. Also, for the heating and cooling system of the hospital, three boilers each with a capacity of 22,000 pounds per hour are considered, so that the steam is used to feed the absorption chiller generator for cooling. Also, the above steam is used for heat exchangers, domestic hot water generators and fan coils. The schematic of the hybrid chiller plant t is shown in Fig. 1.

For the transfer of cooling system fluid, seven pump units are considered with continuous constant flow. Also, controlling the cooling capacity of the building according to the needs of seasons and different hours of the operation is by changing the capacity of the chillers separately as well as switching on and off each chiller.

Table 1. Main equipment located in the mechanical and air handling room of the Heart Center Hospital, Tehran

item	equipment	Numbers of equipment
1	Single effect absorption chiller	3
2	Air cooled screw compressor	2
3	Steam boiler	3
4	Air handling unit	32
5	Pumps of air handling units	7
6	Pumps of fan coil	4
7	Pumps of cooling towers	8
8	Cooling tower	3
9	Domestic hot water generator	4
10	Steam – water heat exchanger for hot water circulation of air handling units and fan coils	3

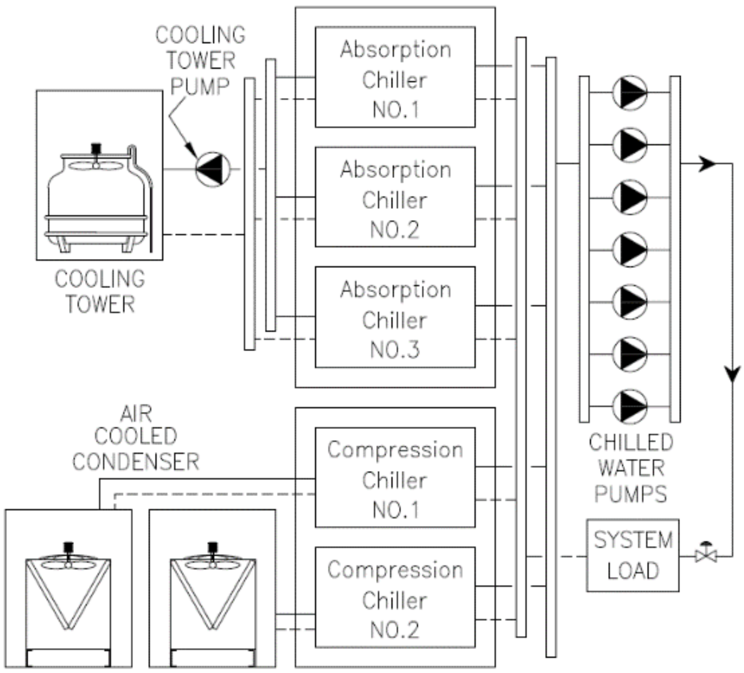

Figure 1. Schematic layout of hospital hybrid chiller plant

3. Data Collection for Understanding the Pattern of Energy Consumption in the Hybrid Chiller Plant

To measure chiller plant parameters including temperature of the outlet and input water of each chillers, temperature of entering and exiting water of cooling towers, the number of chillers in the circuit, the number of compressors in the circuit for Vapor compression chillers and the amount of electricity flow, a field study for data collection has been conducted. All the above-mentioned parameters have been measured at a time interval of 2 hours per day, a total of 4200 field data series has been collected for evaluating the performance of each Vapor compression and absorption chiller for six months.

4. Energy Modeling

In order to study the effect of cooling load sharing strategies on energy consumption in the hybrid chiller plant, a computer model was prepared using eQuest software and the results were compared with the data collected during the field study. The architecture of the building is modeled using the architectural drawings with software, and then according to the mechanical system, the equipment consists of Vapor compression chillers, absorption chillers, hot water generators, boilers and operating fluid pump system, cooling towers, and air-cooled condenser have been modeled.

5. Capacity Control of the Hybrid Chiller Plant According to Cooling Load

To investigate the sequence of operation and time of partial load of chillers on energy consumption in the hybrid chiller plant, two scenarios are considered as follow:

- In scenario-1; the obtained practical data was analyzed in the actual operating conditions of chillers and also the behavior of them at different hours with regard to sequencing and capacity change is indicated.
- In scenario-2, the same system and their cooling load sharing strategies were modeled and optimized in e.Quest software for reducing the energy consumption.

Since chiller compressors are screwed and semi-hermetic and each chiller has four compressors, changing the capacity of chillers during partial loads is as follows:

- On and Off operation of chiller/ compressor
- Using a step control of the slide valve inside the compressors (4 steps of 100-75-50-25%)

Figure 2 shows the algorithm of the computer model.

6. Results and Discussion

As mentioned in the previous section, to investigate the sequence of operation and time of partial load of chillers on energy consumption, two scenarios are considered. In scenario 1, the actual operating conditions of the chiller plant are predicted using a developed computer model. In scenario 2, the sequence of operation and time of partial load of chillers are optimized to minimizing the energy consumption of the plant.

6.1. Scenario 1: Actual Operating Conditions

In this scenario, the cooling costs of the hospital by the mentioned chillers are calculated by examining the statistical practical data in different months and the operating conditions of the mechanical room. Also, during this study, the proportion of absorption and Vapor compression chillers were calculated to provide the cooling load required for the hospital.

The power consumption of screw compressors with its output cooling capacity is not linear during partial loads (BITZER Company, 2017). The electric energy consumption of Vapor compression chillers can be calculated as follow:

$$P = \sqrt{3}VI\cos\emptyset \qquad (1)$$

In that case, $\cos\emptyset$, the coefficient of power of the electric system, is intermittent and equal to 0.85 (Boghosian, 2015). In order to estimate the cooling load due to changes in the load factor during the day and in different seasons, the data recorded in 2-hour intervals have been used. Equation 2 is used to calculate the cooling capacity of each chiller.

$$\mathrm{CL} = 500\dot{\mathrm{v}}\Delta\mathrm{T} \qquad (2)$$

where $\dot{\mathrm{v}}$ is the flow rate of each chiller in gallon per minute, and $\Delta\mathrm{T}$ is the difference in temperature between the evaporator's inlet and outlet each of chiller and in degrees Fahrenheit (ASHRAE Application Handbook, 2016).

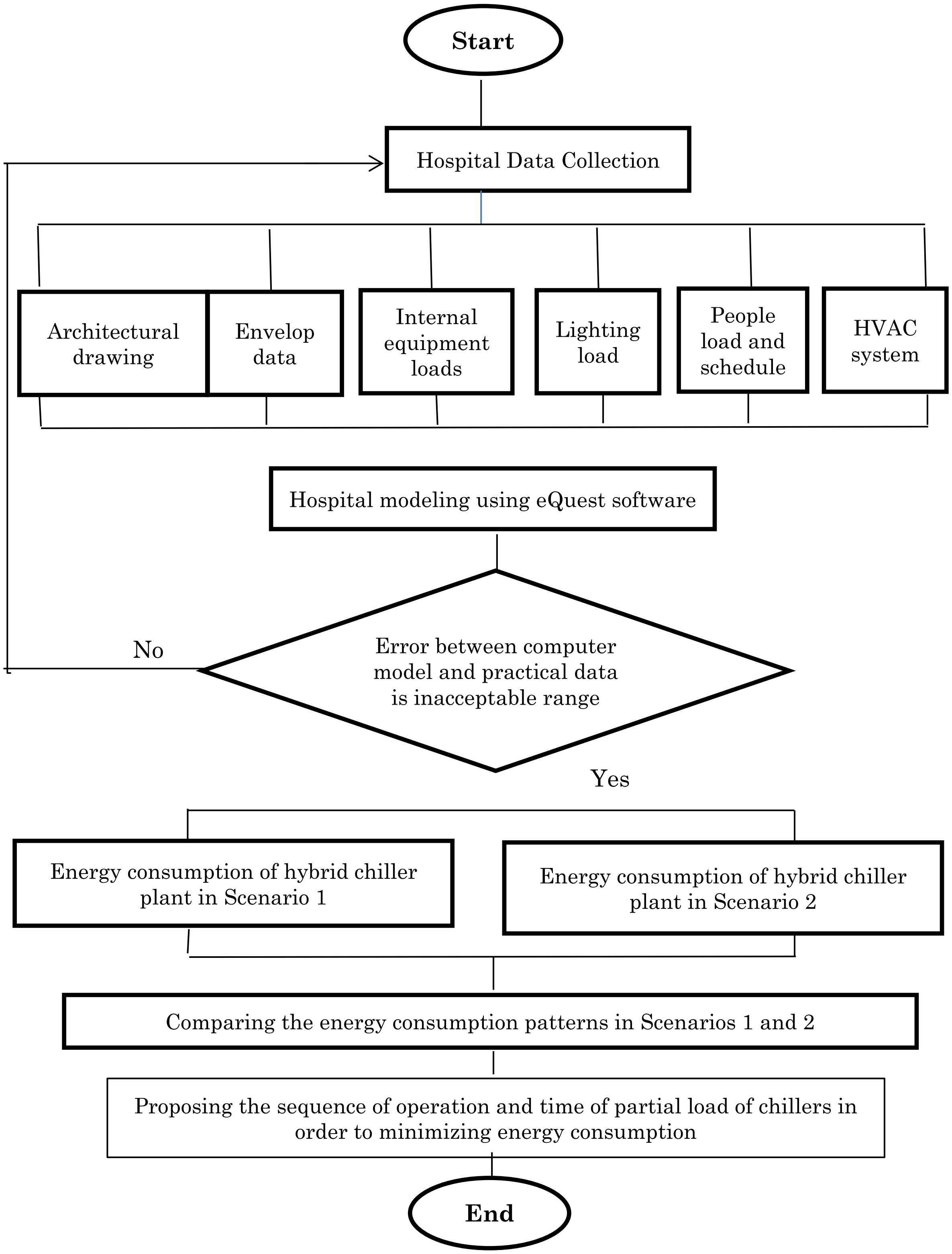

Figure 2. Algorithm of computer model

Regarding the use of steam to supply heat to the absorption chiller generator, it is necessary to estimate the amount of steam used and consequently to estimate the consumption of natural gas. It is not possible to directly estimate steam consumption through the capacity of steam boilers because of various uses of steam such as; a launderette, antiseptic, hot water generation, air conditioning coil heating, etc. Therefore, the amount of natural gas consumed for steam generation with required working pressure from manufacturers of absorption chillers has been calculated. The amount of steam used for each absorption chiller is 10566 pounds per hour and a pressure of 15 pounds per square inch. Regarding the gas thermal value and the efficiency of the boiler burner, the natural gas consumption for each absorption chillers, taking into account the thermal value of natural gas as 8600 kcal / m^3, is equivalent to 0.73 cubic meters per hour per ton of refrigeration for absorption chiller.

The pattern of operation in the circuit of chillers (off and on) varies for month to month. Chillers load pattern for each day of May is shown in Fig. 3.

As seen in the first half of the month, due to the low ambient temperature and cooling load, Vapor compression chillers are off and the cooling load is provided by absorption chillers. The share of each Vapor compression and absorption chiller per May is shown in Figures 4 and 5, respectively.

As it shows, the Vapor compression chiller No. one was off in all the days of the month, other than the 15th day, and did not need to be in operation. Also, this month there is no need for all absorption chillers to be in operation and most of the load is provided by the absorption chillers No. 2 and 3.

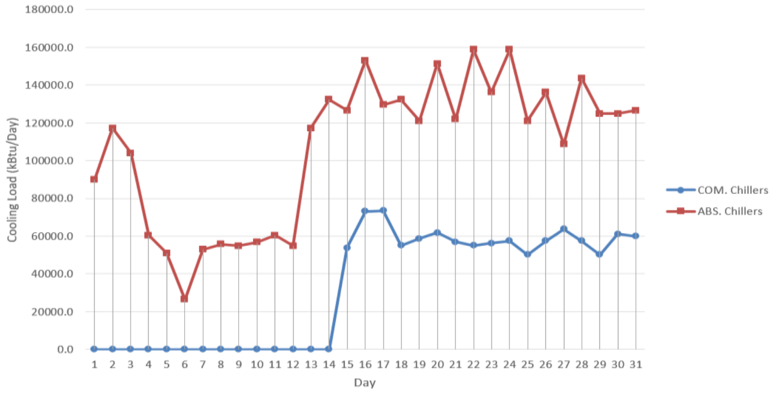

Figure 3. Cooling rate for vapor compression and absorption chillers in May

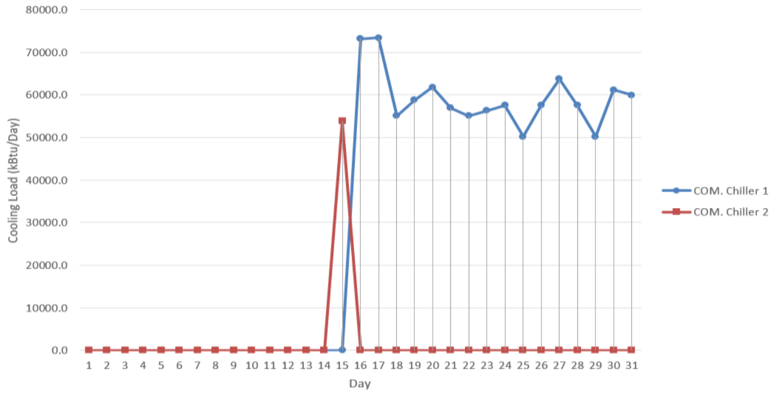

Figure 4. Vapor compression Chillers Cooling load in May

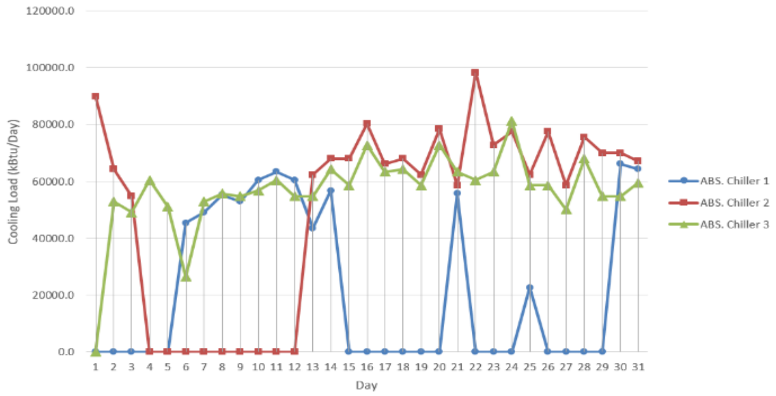

Figure 5. Absorption Chillers Cooling load in May

By reviewing June, with an increase in ambient temperature, all chillers need to be placed in the circuit. Considering the high capacity of absorption chillers over vapor compression chillers, the share of charging of absorption chillers is higher in all months. The chillers load pattern for June is shown in Figure 6.

The share of cooling load in July, August, and September is shown in Fig. 7 to Fig. 17.

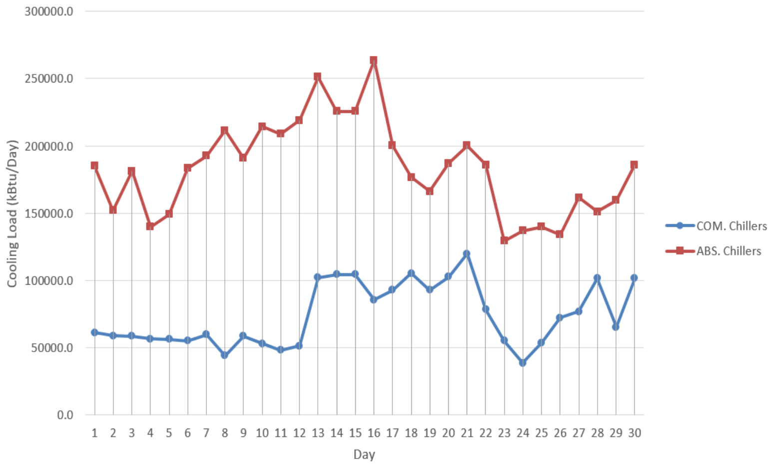

Figure 6. Absorption and vapor compression Chillers Cooling load in Jun

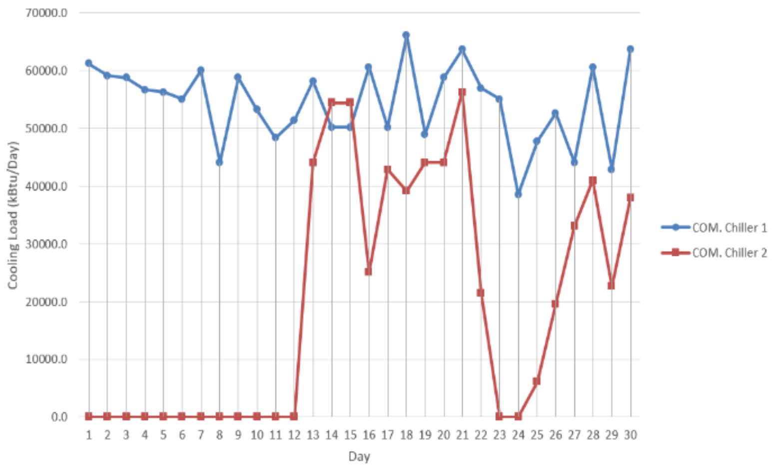

Figure 7. Vapor compression Chillers Cooling load in June

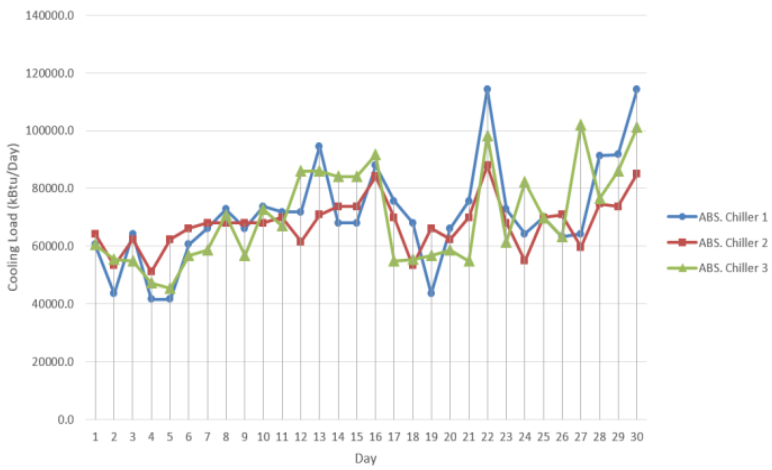

Figure 8. Absorption Chillers Cooling load in June

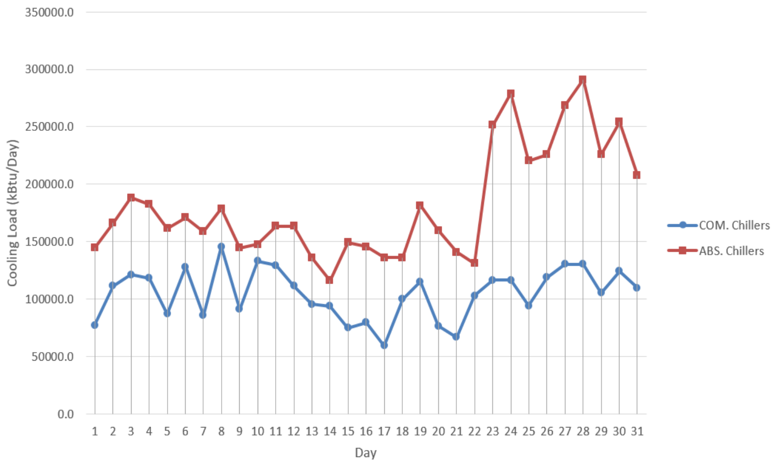

Figure 9. Absorption and vapor compression Chillers Cooling load in July

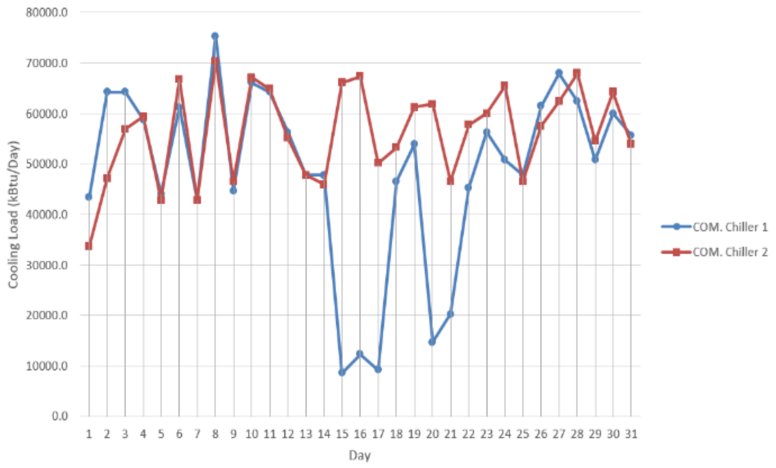

Figure 10. Vapor compression Chillers Cooling load in July

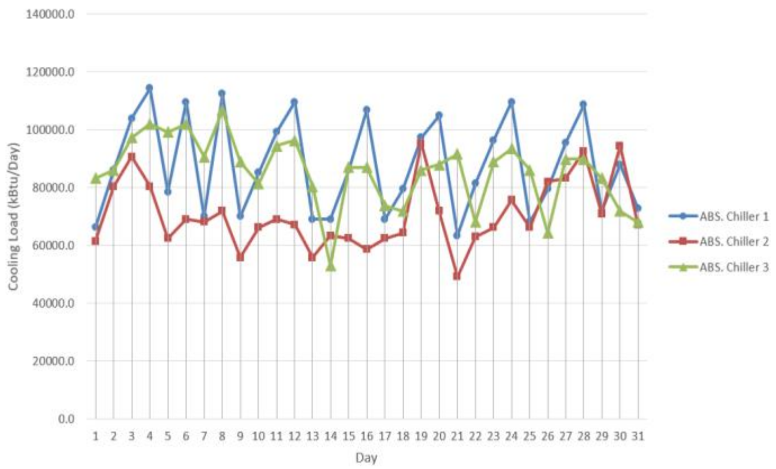

Figure 11. Absorption Chillers Cooling load in July

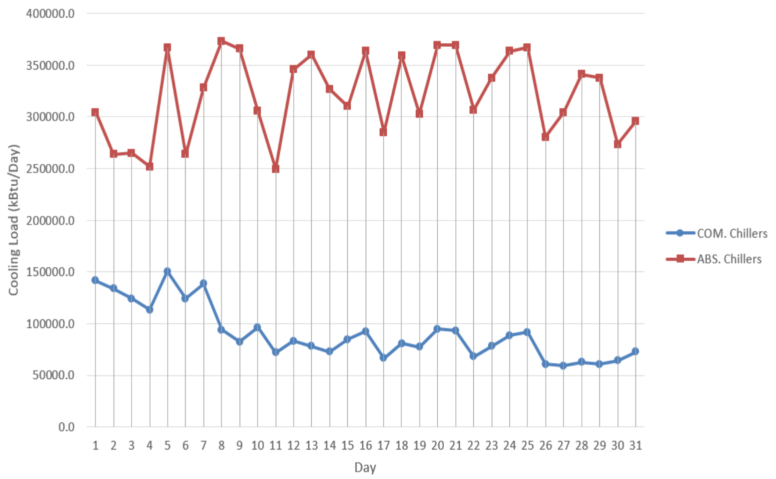

Figure 12. Absorption and vapor compression Chillers Cooling load in August

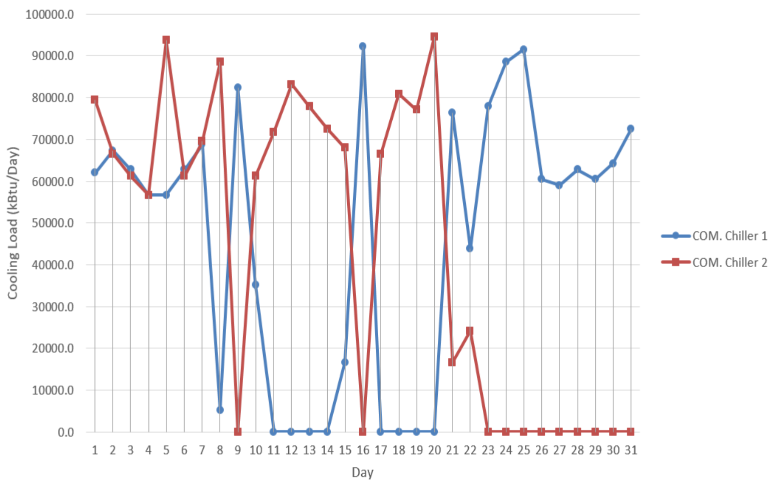

Figure 13. Vapor compression Chillers Cooling load in August

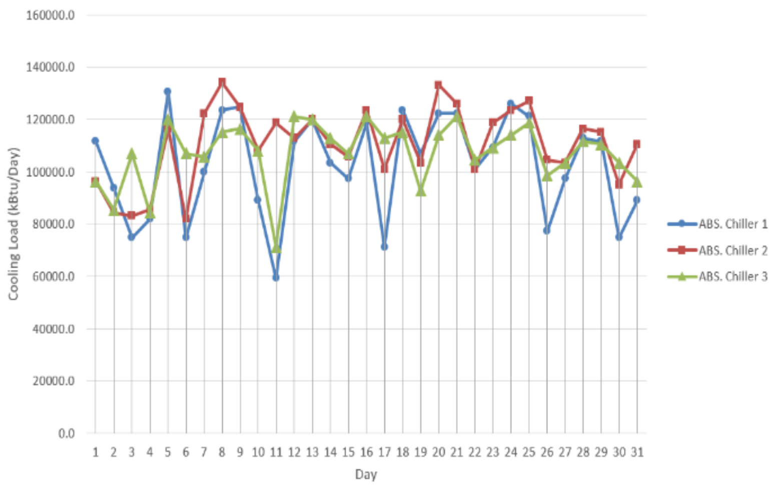

Figure 14. Absorption Chillers Cooling load in August

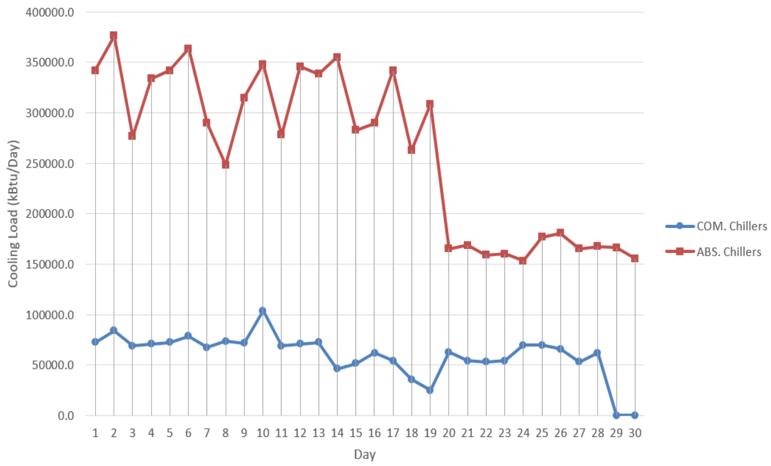

Figure 15. Absorption and Vapor compression Chillers Cooling load in September

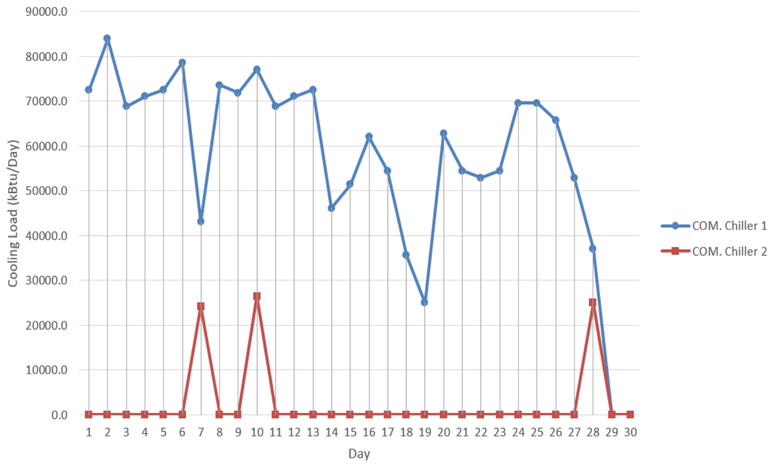

Figure 16. Vapor compression Chillers Cooling load in September

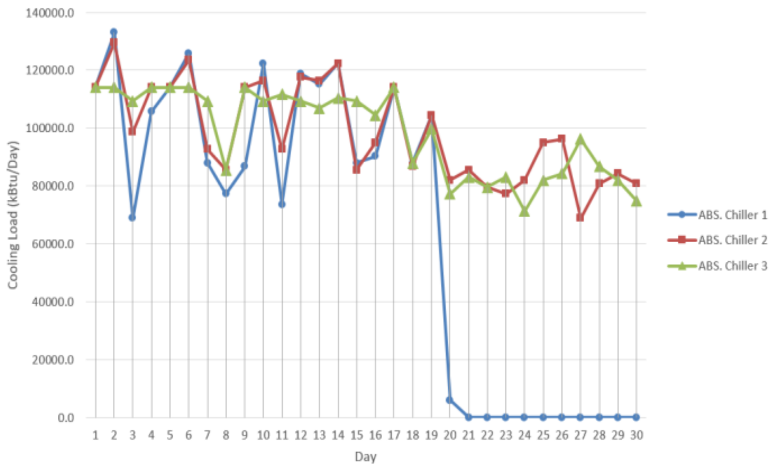

Figure 17. Absorption Chillers Cooling load in September

The variation in the use of Vapor compression chillers No. 1 and 2 in August is significant compared to other months. Also, as seen at the end of September, due to reduced cooling load, both Vapor compression chillers and absorption chiller No. 1 are off and out of the circuit. Regarding equations 1 and 2, the pattern of natural gas consumption and electrical energy can be calculated and is presented monthly in Fig. 18 and Fig. 19.

Also, the amount of cooling load provided by vapor compression and absorption chillers every month is shown in Fig. 20 and Fig. 21, respectively

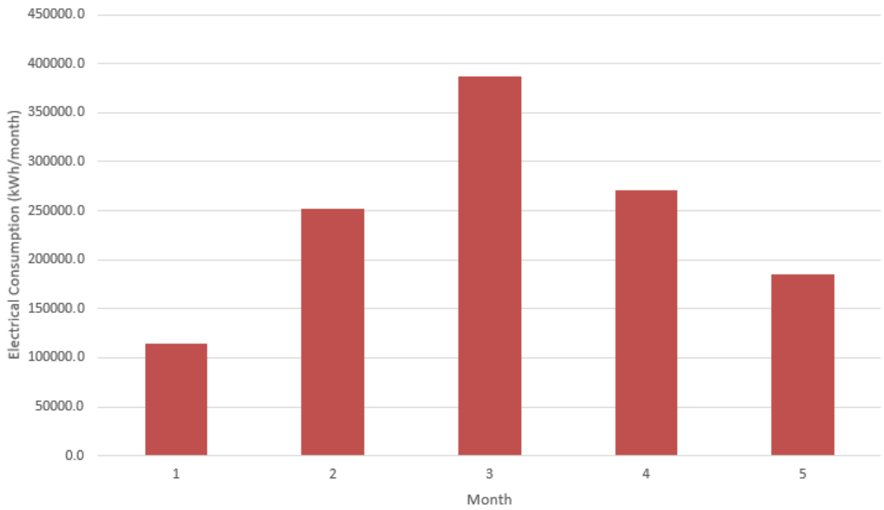

Figure 18. Monthly electrical consumption load for scenario-1

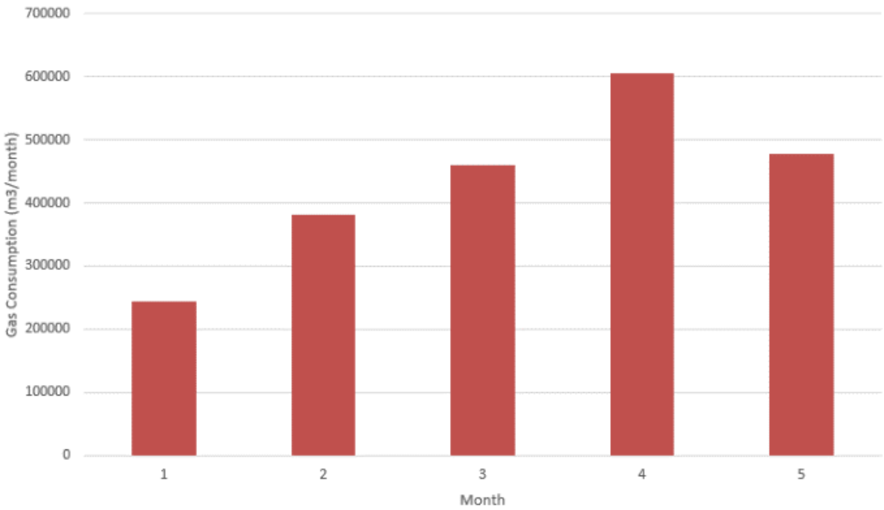

Figure 19. natural gas consumption in scenario 1

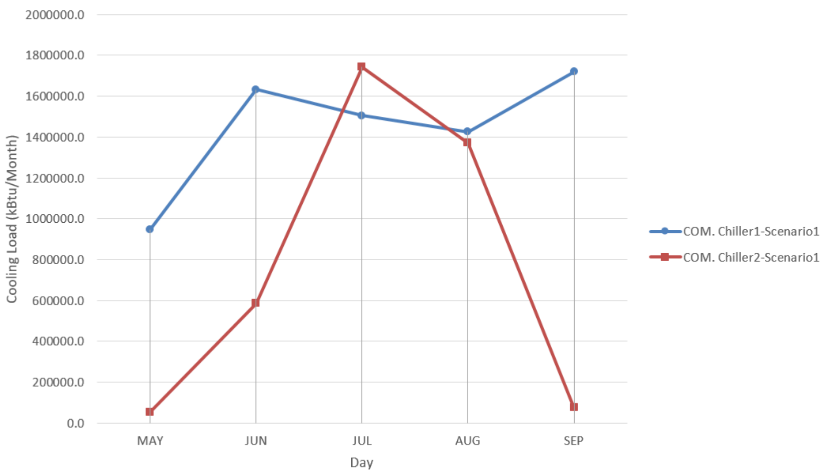

Figure 20. The amount of cooling load provided by vapor compression chillers (scenario-1)

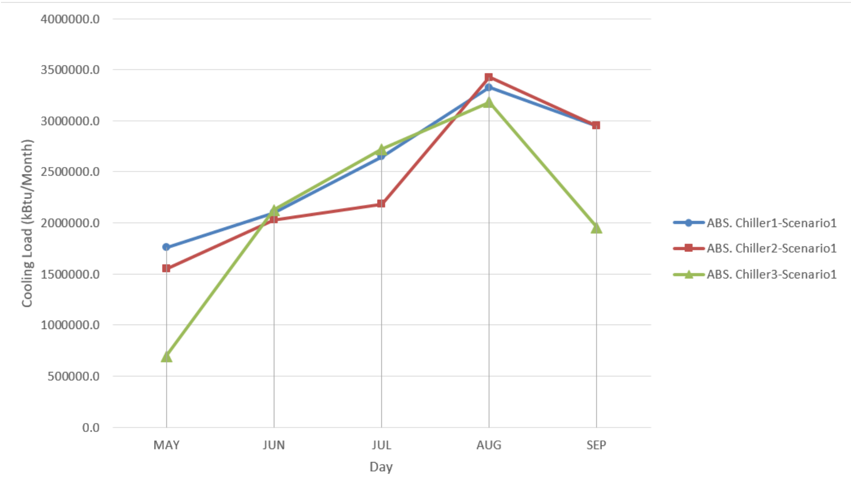

Figure 21. The amount of cooling load provided by absorption Chillers (scenario-1)

6.2. Scenario 2: Optimal Sequence of Operation and Time of Partial Load (Software Modeling)

By modeling the mentioned hospital in the eQuest software, the behavior of the system is investigated and the optimal sequence of operation and time of partial load in chiller plant can be obtained.

First, the architecture of the building and the central mechanical room system were modeled with all heating and cooling equipment and then, the amount of cooling load produced monthly by each chiller was evaluated.

The method for calculating the thermal and refrigeration load in eQuest software is presented by DOE-2(DOE-2 Engineering Manual, 1982). Observed heat in the building to calculate the cooling load includes the following heat sources:

- Heat transfer (which includes the displacement of energy from walls, ceilings, windows, taking into account the effect of thermal storage of walls and ceilings on the displacement of energy, doors, etc.)
- Heat produced by the sun's radiation.
- Heat produced by the lighting system
- Heat produced by internal equipment
- Heat produced by the activity of individuals (DOE-2 Engineering Manual, 1982)

Also, to calculate the cooling load provided by chillers at partial load times, the ASHRAE 90.1 standard was used (Goel, Rosenberg & Eley, 2017). Equation 3 represents the cooling load produced by chillers at partial load times:

$$Q_{available} = CAP - FT \times Q_{rated} \quad (3)$$

For air-cooled chillers:

$$CAP - FT = a + b \times T_{chws} + c \times T_{chws}^{2} + d \times T_{odb} + e \times T_{odb}^{2} + f \times T_{chws} \times T_{odb} \quad (4)$$

For water-cooled chillers:

$$CAP - FT = a + b \times T_{chws} + c \times T_{chws}^{2} + d \times T_{cws} + e \times T_{cws}^{2} + f \times T_{chws} \times T_{cws} \quad (5)$$

It shall be noted that constrains on parameters in equations 3 to 5 are as follows:

- T_{chws} (Chilled water supply):min=40°F, max=54°F
- T_{cws} (Cooling water supply): min=60°F, max=85°F
- T_{odb} (Outdoor dry bulb temperature):min=40°F, max=115°F

The values a, b, c, d, e, f for single-effect absorption chillers and screw-air-cooled-chillers are presented in Table 2.

Table 2. Part load coefficient for air-cooled screw chillers (Goel, Rosenberg & Eley, 2017)

parameter	Air cooled screw chiller	Single effect absorption chiller
a	-0.09464899	0.723412
b	0.03834070	0.079006
c	-0.00009205	0.000897
d	0.00378007	-0.025285
e	-0.00001375	-0.00048
f	-0.0015464	-0.00276

The amount of cooling energy provided by Vapor compression chillers and absorption chillers in the 2nd Scenario is shown in Figures 22 and 23.

As shown in Figure 22, the amount of energy supplied by the No. 2 vapor compression chiller, compared to the vapor compression chiller No.1, is lower in all months. Also, the amount of cooling load provided by three absorption chillers is in uniform ratio. The consumption of natural gas and electric energy in scenario-2, estimated by eQuest software, is presented in Figures 24 and 25.

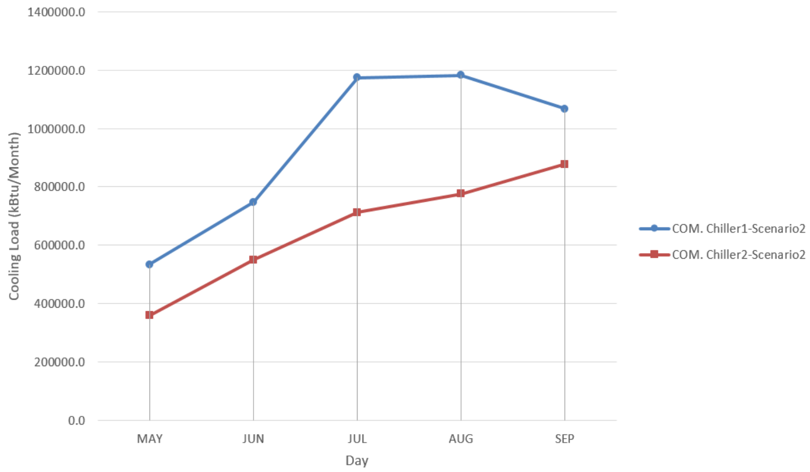

Figure 22. Cooling loads of Vapor compression chillers in scenario-2

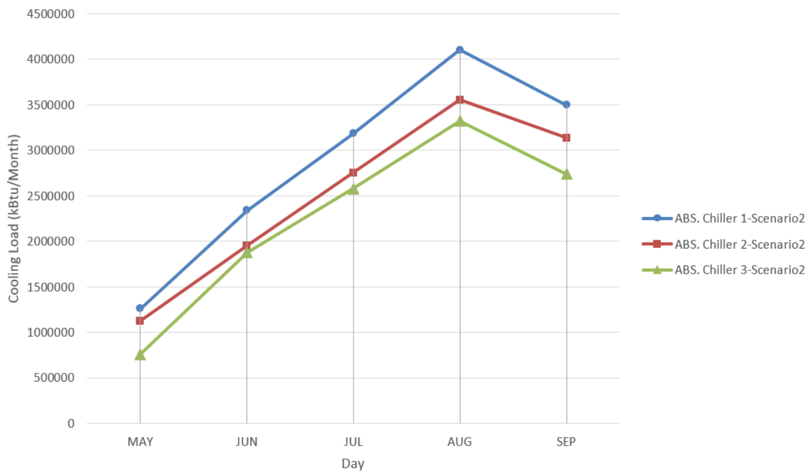

Figure 23. Absorption chillers cooling load in scenario-2

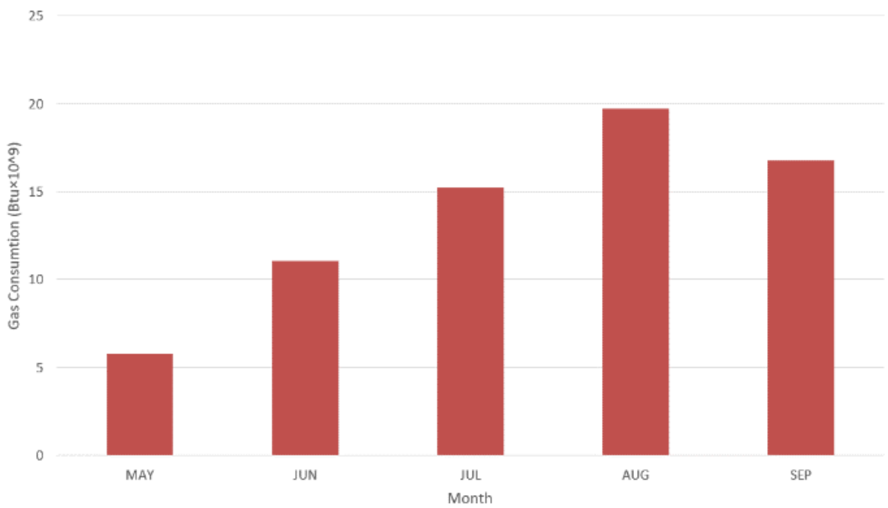

Figure 24. The amount of natural gas consumption to supply refrigeration load in scenario-2

As the curves present, electricity consumption in July, August, and September was modest, but gas consumption in August was the highest.

6.3. Validation of Modeling Results

For validation of the modeling results (scenario-2), the total cooling load provided by each of the five vapor compression and absorption chillers in both scenarios-1& 2, was compared in Table 3. The low amount of cooling load disruption over a total of five months between scenario-1 and scenario-2 represents the accuracy of the software model.

7. Conclusion

The difference between the cooling loads provided by each of the five vapor compression and absorption chillers in scenarios 1 and 2is high. One of the reasons for this is that the vapor compression chiller No. 2 is off during the month, which resulted in a share of cooling load being provided by other chillers.

In scenario 2, the required cooling load in the building is provided by all chillers using the part - load capacity control method. Regarding the validation and the acceptable difference in the load -bearing capacity provided by absorption and Vapor compression chillers during the five months as previously mentioned, the possibility to compare the costs of natural gas and electricity is provided.

In the case of optimal control of the operation of chillers (scenarios 2), by controlling the share of load between Vapor compression and absorption chillers, it is observed that the consumption of natural gas and electrical energy has decreased compared to the scenario-1 (Figure 26 and 27).

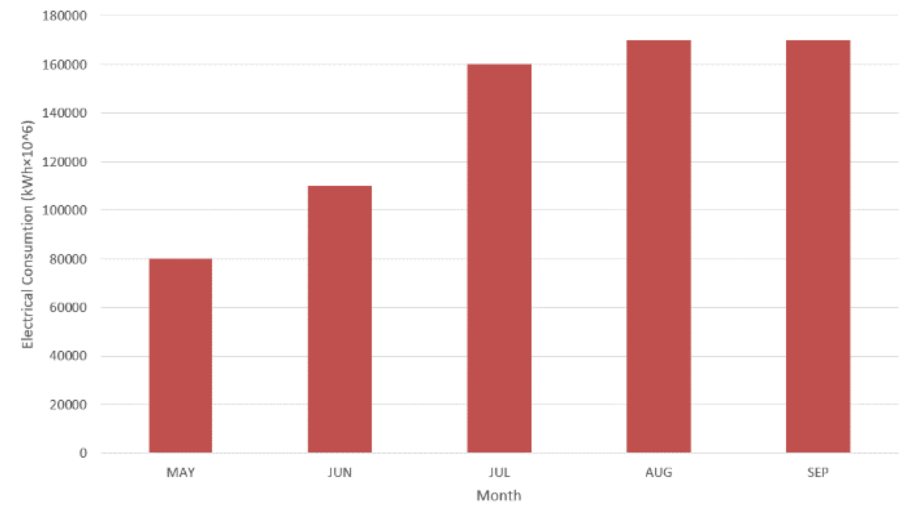

Figure 25. The amount of electric power used to provide cooling in scenario-2

Table 3. Comparison of total load capacity provided by absorption and vapor compression chillers in both scenarios-1& 2

Month	Data	Total cooling load kBtu/month	Deviation
May	Experimental data	5006866	19.4%
	Software model	4035191	
June	Experimental data	7545542	1.1%
	Software model	7464022	
July	Experimental data	10804538	3.7%
	Software model	10401222	
August	Experimental data	12935127	-1.6%
	Software model	11319470	
September	Experimental data	9653666	-19.3%
	Software model	11319470	
For 5 Months	Experimental data	46674183	0.9%
	Software model	46155032	

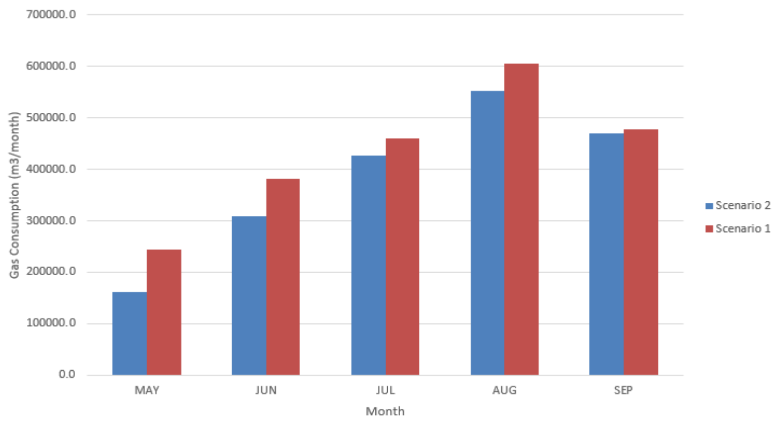

Figure 26. Comparison of natural gas consumption between two scenarios-1 & 2

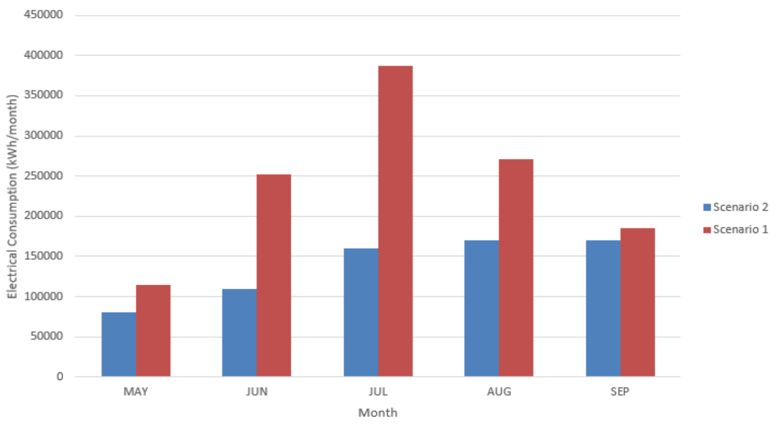

Figure 27. Comparison of electricity consumption between two scenarios-1 & 2

The proportion of electric power consumption is lowered compared to natural gas consumption.

The percentage of electricity and natural gas consumption differences per month is presented in Table-4.

Also, when comparing energy consumption over five months, the amount of electricity consumption decreased by 42.9% and for natural gas consumption, it was 11.4%. As a result, the sequence of the chiller function and how they are placed in the circuit during a partial load, at a time when the combination of single-effect absorption chillers and screw Vapor compression are used in one mechanical room, is in highest importance in viewpoint of energy saving.

Table 4. Comparison of differences in electric energy consumption and natural gas consumption between scenarios 1 & 2

	Electrical Energy	Natural gas
May	30.1%	6.33%
June	56.4%	18.7%
July	58.6%	7.3%
August	37.3%	8.6%
September	8.0%	1.7%
For 5 months	42.9%	11.4%

8. Nomenclature

Symbols

a	Part load coefficent
b	Part load coefficent
c	Part load coefficent
CAP-FT	Cooling capacity adjustment factor
CL	Cooling capacity
d	Part load coefficent
e	Part load coefficent
f	Part load coefficent
GPM	Gallon per minut
I	Electrical current
P	Electrical power
Q	Cooling capacity
t	Time
T	Temperature
$\dot{v}$	Water flow (gpm)
V	Voltage
W	Weighting factor
γ	Weighing factor
φ	Electrical power coefficient
subscript	
chws	Chilled water supply
cws	Cooling water supply
i	Time range
odb	Outdoor dry bulb temperature

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