Energy savings potential in air conditioners and chiller systems

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Abstract: In the current paper we quantified and evaluated the energy saving potential in air conditioners and chiller systems. We also showed how to reduce the cost of air conditioners and chiller systems in existing facilities on the basis of payback periods. Among the measures investigated were: 1) installing higher efficiency air conditioners, 2) installing higher efficiency chillers, 3) duty cycling air conditioning units, and 4) utilizing existing economizers on air conditioning units. For each method, examples were provided from Arizona, USA. In these examples, the amount of saved energy, the financial evaluation of this energy, and the investment cost and pay back periods were calculated.

Key words: Energy saving, HVAC systems, air conditioner systems, chiller systems

1. Introduction

Many plants have chillers that provide cooling for various plant processes. Chillers consist of a compressor, an evaporator, an expansion valve, and a condenser. The evaporator is a tube-and-shell heat exchanger used to transfer heat to evaporate the refrigerant. The expansion valve is usually some kind of regulating valve (such as a pressure, temperature, or liquid-level regulator) according to the type of control used. The condenser is most often a tube-and-shell heat exchanger that transfers heat from the system to the atmosphere or to the cooling water [1].

More than six million unitary air conditioners used in residences and smaller commercial buildings are sold per year. Manufacturers must comply with the minimum efficiency standards for unitary equipment, meaning that very inefficient models can no longer be produced and sold in the United States. However, there is still a wide efficiency range available in the marketplace. For example, for split system air conditioners under 19.05 kWh in cooling capacity, the current minimum standard is a seasonal energy efficiency ratio (SEER) of 10.0. New models, on average, have a SEER of about 11.0, but the top-rated models have a SEER of 15.0 or greater. Thus, there is substantial potential to cut electricity use and pollutant emissions associated with such use by promoting the purchasing of highly efficient unitary air conditioners [2].

Air conditioners and chiller systems are important and high-quality use options of electricity. For example, approximately 50% of the energy used by the commercial sector in South Africa is utilized for air-conditioning [3,4]. This clearly shows that these systems have large potential for energy savings [5]. The operating costs of a facility could be improved upon if the air conditioners and/or chillers of the facility are made more energy efficient. This will result not only in monetary savings, but also in less greenhouse gases released into the

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atmosphere [3,4]. Studies have shown that energy savings of around 30% can be achieved in an air conditioner system through retrofit options in existing facilities without compromising the indoor comfort [3]. The greatest potential for reducing energy consumption exists in the efficient design and operation of the chilled water plant and air-conditioning system [6–8].

The energy-saving options investigated in previous studies were compressed-air systems [9], boiler systems [10,11], pumps [12], and lighting systems [13]. In the current study, the energy-saving potential in air conditioners and chiller systems is evaluated and quantified. The main aim of this study is to raise awareness and show the considerable energy and cost-saving opportunities in air conditioners and chiller systems.

2. Energy- and cost-saving potential in air conditioners and chiller systems

2.1. Installing higher-efficiency air conditioners

Presently, there are many packaged air conditioning units at many facilities used for cooling office and production areas that were manufactured in the 1990s. Today, manufacturers produce air conditioners with much higher efficiencies than those currently installed at many facilities. The energy cost savings resulting from these new higher-efficiency units will help pay for the replacement of the older air conditioners.

Energy savings are due to the higher efficiency rating of the new air conditioners. The monthly demand savings, DS, to be achieved by installing new high-efficiency air conditioners can be estimated as the difference between the current power demand, CED, and the proposed power demand, PED:

$$DS = CED - PED. \tag{1}$$

The CED and PED values can be estimated as follows:

$$CED = N \times (CC/SEER_{ci}) \times K1, \tag{2}$$

$$PED = N \times (CC/SEER_{pi}) \times K1, \tag{3}$$

where N is the number of units, CC is the cooling capacity (kW/h), SEER is the seasonal energy efficiency ratio (kW h^{-1} W^{-1}), K1 is the energy conversion factor (0.001 kW/W), ci is the current SEER rating, and pi is the proposed SEER rating.

The annual usage savings, US, can be estimated as the difference between the current energy usage, CEU, and the proposed energy usage, PEU:

$$US = (CED - PED) \times CLH = CEU - PEU, \tag{4}$$

where CLH is the cooling load hours (h/year).

In order to estimate the annual cost savings due to usage reduction, UCS, the following equation will be used:

$$UCS = US \times (\text{average usage cost}). \tag{5}$$

The estimated demand savings, EDS, is calculated as:

$$EDS = DS * CF. \tag{6}$$

In order to estimate the annual cost savings due to demand reduction, DCS, the following equation will be used:

$$DCS = DS \times (\text{average demand cost}) \times M \times CF, \tag{7}$$

where M is the number of months the A/C units are running and CF is the coincidence factor.

The total annual cost savings for these units, CS, is estimated as:

$$CS = UCS + DCS. \tag{8}$$

The total annual energy savings (ES), in kWh/year, are estimated as:

$$ES = US. \tag{9}$$

It is recommended that new air conditioners be installed only when existing units reach the end of their lifetime because the cost of implementation is based on the cost difference between the existing air conditioners and the new higher-efficiency air conditioners.

2.2. Installing higher-efficiency chillers

Some facilities have air-cooled chillers that are dedicated to different processes. The air-cooled chillers (operating on CFC-11 or CFC-12) are inefficient when compared with current water-cooled chiller technology (operating on HCFCs or HFCs). The air-cooled chillers provide cooling at approximately 1.40–1.75 kW/t. Current water-cooled chiller technology of the same size range provides cooling at approximately 0.46–0.65 kW/t [6]. Replacement of the existing chillers with modern, high-efficiency water-cooled chillers will significantly reduce electrical energy consumption and the electrical demand charge. It is recommended that the chillers be replaced when the existing chillers reach the end of their useful life. The proposed chillers would employ a chilled water loop to provide space cooling and would require the installation of a cooling tower rated for the same tonnage. Savings are found by subtracting the estimated energy to run the current chillers from the estimated energy to run the new chiller.

The cooling tower required for a water-cooled chiller will affect the demand savings. The monthly demand savings are estimated from the following relation:

$$DS = (CC \times EC) - (PC \times EN) - (HP1/EFF1) - (HP2/EFF2), \tag{10}$$

and the annual energy usage savings are estimated as:

$$US = DS \times HL, \tag{11}$$

where CC is the current cooling capacity of the chillers at full load (t), EC is the estimated average energy to run the current chiller at full load (kW/t), PC is the proposed cooling capacity of the new chiller at full load (t), EN is the estimated energy to run the new chiller at full load (kW/t), HL is the estimated equivalent operating hours at full load (h/year), HP1 is the power rating of the cooling tower fan motor, HP2 is the power rating of the cooling tower pump motor, EFF1 is the motor efficiency for the high-efficiency totally enclosed fan cooled (TEFC) motor, and EFF2 is the motor efficiency for the high-efficiency TEFC motor.

The annual energy cost savings, ECS, are calculated by:

$$ECS = DS \times (\text{number of months}) \times (\text{average demand cost}) + US \times (\text{average usage cost}). \tag{12}$$

The total annual energy savings are equal to the usage savings.

The cost savings will be affected by the cooling tower water usage. The quantity of make-up water required is dependent upon bleed off and evaporation rates.

The bleed-off rate of cooling, BR, can be estimated as:

$$BR = ER/(CR - 1), \tag{13}$$

where CR is the concentration ratio of bleed-off water to make-up water. ER is the evaporation rate.

The water consumption (in m^3/year), WU, can be estimated as:

$$WU = (BR + ER) \times N \times H, \tag{14}$$

where N is the number of cooling towers and H is the estimated annual hours (h/year).

The water consumption cost, WC, can be estimated as:

$$WC = WU \times (CW + CS), \tag{15}$$

where WC is the water consumption cost (\$/year), CW is the cost of water (\$/m^3), and CS is the cost of sewage disposal (\$/m^3).

Therefore, the total cost savings, TCS, are found as:

$$TCS = ECS - WC. \tag{16}$$

It is recommended that new air conditioners be installed only when existing units reach the end of their lifetime because the cost of implementation is based on the cost difference between the air-cooled chillers and the water-cooled chillers.

2.3. Duty cycling air conditioning units

Most air conditioning systems are designed for peak load conditions and consequently these systems are usually moving much more air than needed. Therefore, they can sometimes be shut down for short periods each hour, typically 15 min, without affecting occupant comfort [5]. These air conditioning units can be subgrouped to prevent random on and off cycling, which contributes significantly to the monthly demand costs. The control system for each subgroup will prevent one unit in the group from running and keep the rest of the A/C units running for a longer period of time. This function is called forced duty cycling. Overall demand costs can then be reduced by limiting the maximum load in each of these groups.

If the duty cycling control is used during peak times, one unit from each group will be turned off.

The monthly demand savings, MDS, are estimated as:

$$MDS = (\text{total unit tonnage}) \times (\text{load factor})/SEER \times (\text{cooling capacity per ton}) \times (0.001 kW/W). \tag{17}$$

The above value is the maximum possible demand savings, which can be expected to occur during the summer months (cooling) and the winter months (heating). An adjustment factor is used for the remaining months for both cooling and heating.

The total annual cost savings are estimated as:

$$CS = [(\text{peak months}) \times (\text{total } MDS) + (\text{remaining operation months}) \times (AF \times MDS)] \times (\text{average demand cost}), \tag{18}$$

where AF is the adjustment factor.

The estimated implementation cost (IC) associated with this recommendation includes programmable controllers, relays, and the installation labor for the three groups:

$$
\begin{aligned}
IC \quad = \quad & (\# \text{ of controllers} \times \text{controller price}) + (\# \text{ of controllers} \times \text{installation cost}) \\
& + (\# \text{ of relays} \times \text{controller price}) + (\# \text{ of relays} \times \text{installation cost}),
\end{aligned} \tag{19}
$$

2.4. Utilizing existing economizers on air conditioning units

Utilizing the economizers on the roof-top mounted air conditioning units by seasonally adjusting the damper setting can save energy and money. The dampers should be open to 100% capacity during the winter. This will reduce space cooling energy usage during these months.

Economizers are essentially a duct and damper system that allows fresh outside air to be used directly for space cooling whenever outdoor temperature and humidity levels are favorable. By using cool outside air whenever possible, the energy usage by the mechanical cooling units can be significantly reduced. The larger the internal gain (heat from equipment, people, etc.) is, the more effective the economizers and the greater the potential savings are as compared with mechanical cooling.

Potential savings are based on the assumption that outside air can be used to provide space cooling during the winter months when the temperatures are cooler and the relative humidity is below 50%. This outside air could then be utilized directly without any need for humidification conditioning.

The proposed total energy usage savings when utilizing the economizers can be estimated from the following relationship:

$$
US = \{N \times V \times C_p \times \rho \times (T_s - T_o) \times UF \times k2 \times H\}/COP, \tag{20}
$$

where N is the number of air conditioning units, V is the total air flow through all air conditioning units (m^3/h), C_p is the specific heat of air (J/kg K), ρ is the density of air (kg/m^3), T_s is the average temperature of air supplied to the cooling coil under present conditions (K), T_o is the average temperature of outside air during winter (K), UF is the fraction of operation time that units operate (usage factor; no units), k2 is the conversion constant (1/3,600,000 kWh/J), H is the number of hours in winter (3600 h), and COP is the coefficient of performance (no units).

The weighted average temperature of air supplied to the cooling coil under present conditions, T_s, results from mixing outside air with indoor return air and is estimated as:

$$
T_s = (T_o \times \text{present damper setting}) + (T_r \times [1 - \text{present damper setting}]). \tag{21}
$$

The cost savings, CS, are calculated as follows:

$$
CS = US \times (\text{average usage cost/kWh}). \tag{22}
$$

The total annual energy savings are equal to the usage savings.

The existing roof-top air conditioning units are equipped with the necessary dampers to utilize the economizer cycle, so there will be no implementation cost; the cost savings are immediate.

3. Sample studies and results
3.1. Case study 1: Installing higher-efficiency air conditioners

There are 16 packaged air conditioning units at a facility used for cooling office and production areas. The units were manufactured in 1985. It was reported that cooling is used 8 months out of the year in the office and production areas.

Based on the specifications indicated on the equipment, the air conditioning units have cooling capacities of fifteen tons each. The amount of time that the production units are operating is estimated as 3,241 hr/yr based on a usage factor of 0.555 [14]. For calculation purposes the average SEER of the existing air conditioners is 0.002462 kW/hr/W. For each type of unit it is very common to find newer units with a SEER of 0.003517 kW/hr/W. Demand charge is \$6.38/kW and usage charge is \$0.0552/kWh for this facility. CC is 52.768 kW/hr.

3.1.1. Sample calculation

Demand and usage savings from this replacement program will be determined on an annual basis using the estimate of the number of full load equivalent operating hours (55.5% of actual operating hours). Demand and cost savings will be determined based on the actual billings for the past year. The current and proposed monthly power demands are estimated as in Eqs. (2) and (3).

CED $= 16 \times [(52.768 \text{ kW/h}) / (0.002462 \text{ kW h}^{-1} \text{ W}^{-1})] \times (0.001 \text{ kW/W})$

CED = 342.86 kW

PED $= 16 \times [(52.768 \text{ kW/h}) / (0.003517 \text{ kW h}^{-1} \text{ W}^{-1})] \times (0.001 \text{ kW/W})$

PED = 240 kW

Therefore, the monthly power demand savings are estimated as in Eq. (1).

DS = 342.86 - 240 = 102.86 kW

The annual usage savings are estimated as in Eq. (4).

US = (102.86 kW) $\times$ (3241 h/year) = 333,369 kWh/year

The annual usage cost savings are calculated as in Eq. (5).

UCS = (333,369 kWh/year) $\times$ (\$0.0552/kWh)

UCS = \$18,402/year

The estimated demand savings are calculated as in Eq. (6).

EDS = 102.86 kW $\times$ 0.555

EDS = 57.1 kW

The annual cost savings due to demand reduction can be calculated from Eq. (7) as follows.

DCS = (102.86 kW) $\times$ (\$6.38/kW) $\times$ (8 months/year) $\times$ (0.555)

DCS= \$2914/year

The total annual cost savings for these units are estimated as in Eq. (8).

CS = \$18,402/year + \$2914/year

CS = \$21,316/year

The total annual energy savings are estimated as in Eq. (8).

ES = 333,369 kWh/year

3.1.2. Implementation cost

The average cost to replace the existing units with higher-efficiency ones is approximately \$500/unit more than the lower-efficiency unit, based on current market costs and manufacturers quotes. Therefore, the total implementation cost difference for replacing the existing air conditioners with the new high-efficiency air conditioners would be about \$500 per unit $\times$ 16 units, for a total cost of \$8000. The cost savings, \$21,316/year, will pay for the total estimated implementation cost difference of \$8000 within 5 months.

3.2. Case study 2: Installing higher-efficiency chiller

A facility has an air-cooled chiller that is estimated to be operating at best at an average value of 1.67 kW/t. Current water-cooled chiller technology of the same size range would provide cooling at approximately 0.60 kW/t. HP1, the power rating of the cooling tower fan motor, is 3.73 kW (5 hp). HP2, the power rating of the cooling tower pump motor, is 1.492 kW (2 hp). EFF1, the motor efficiency for the high-efficiency 3.73-kW (5 hp) TEFC motor, is 0.890. EFF2, the motor efficiency for the high-efficiency 1.492-kW TEFC motor, is 0.853. The demand charge is $7.344/kW and the usage charge is $0.070/kWh for this facility. The concentration ratio of bleed-off water to make-up water is 3. Cooling capacity is 70 t, and calculated power is 115 kW. According to plant personnel, the chillers operate 3000 h/year and the estimated hours at full load are 1500 h.

3.2.1. Anticipated savings

Savings are found by subtracting the estimated energy to run the current chiller from the estimated energy to run the new chiller.

Equivalent full-load operating parameters will be used in the calculations. Equivalent full-load hours are estimated as 50% of actual operating hours. The cooling tower required for a water-cooled chiller will also affect the demand savings. The monthly demand savings, DS, are estimated from Eq. (10) as follows.

At full load the demand savings for installing a new 70-t water-cooled chiller are found as:

DS = (70 t) × (1.67 kW/t) – (70 t) × (0.60 kW/t) – ((3.73 kW/0.890)) – ((1.492 kW/0.853)),

DS = 68. 96 kW/month.

The total annual energy usage savings are then found as in Eq. (11).

US = (68.69 kW) × (1500 h/year)

US = 103,440 kWh/year

The annual energy cost savings are calculated as in Eq. (12).

ECS = (68.96 kW/month)(12 months/year)($7.344/kW) + (103,440 kWh/year)($0.070/kWh)

ECS = $13,318/year

The annual energy savings are equal to usage savings, 103,440 kWh/year.

Cost savings will be affected by cooling tower water usage. The quantity of make-up water required is dependent upon bleed-off and evaporation rates. The evaporation rate of the cooling tower can be estimated as 0.009 m^3 min^{-1} 100 t^{-1}. Thus, the evaporation rate, ER, of the cooling tower required is:

ER = (0.009 m^3 min^{-1} 100 t^{-1})× (70 t) × (60 min/h),

ER = 0.378 m^3/h.

The bleed-off rate of the cooling tower [15], BR, can be estimated as in Eq. (13).

BR = 0.378 m^3/h / (3 – 1)

BR = 0.189 m^3/h

The water consumption in m^3/year can be estimated as in Eq. (14).

WU = (0.189 m^3/h + 0.378 m^3/h) × 1 × 1,500 h/year

WU = 850.5 m^3/year

The average cost of water is $0.545/$m^3$ and the average cost of sewage disposal is $0.196/$m^3$. The water consumption cost can be estimated as in Eq. (15).

WC = (850.5 m^3/year) × ($0.545/m^3 + $0.196/m^3)

WC = $630/year

Therefore, the total cost savings are found as in Eq. (16).

TCS = $13,318/year – $630/year

TCS = $12,688/year

3.3. Implementation cost

Based on manufacturer quotations, a single water-cooled chiller and a cooling tower in the size range that is required for this plant may be installed for about $2500 more than the cost to replace the existing chillers with new air cooled chillers. With current electricity prices and without considering interest, the implementation cost should be offset by energy usage savings within about 3 months.

3.4. Case study 3: Duty cycling air conditioning units

A production facility has fifteen 15-t packaged air conditioning units (heat pumps) for cooling and heating the production and warehouse areas. These air conditioning units can be subgrouped to prevent random on and off cycling, which significantly contributes to the monthly demand costs. Cooling at this facility is used 8 months of the year; heating is used 3 months. The average COP of the A/C units at this facility is 2.22 (with a SEER of 0.002227 kW h^{-1} W^{-1}). The demand charge is $6.38/kW for this facility. CC is 52.717 kW/h, and the load factor is 0.85.

3.4.1. Anticipated savings

The fifteen 15-t units can be divided into three groups of five. The following contains relative information about the A/C units.

Random running of the A/C units causes all of them to contribute to demand costs because the monthly demand charge is based on the greatest power draw within any 15-min interval. If the duty cycling control is used during peak times, one unit from each group will be turned off. Thus, demand savings will equal the electricity demand of three 15-t units.

The monthly demand savings are estimated as in Eq. (17).

MDS = (45 t) × (0.85)/(0.002227 kW h^{-1} W^{-1})× (3.5172 kW h^{-1} t^{-1})× (0.001 kW/W)

MDS = 60.39 kW

The above value is the maximum possible demand saving that can be expected to occur in 4 months during the summer and 1 month in winter (heating). An adjustment factor of 0.8 is used for the remaining 6 months for both cooling and heating.

The total annual cost savings are estimated as in Eq. 18.

CS = [(5 months) × (60.39 kW) + (6 months) × (0.8 × 60.39 kW)] × ($6.38 / kW)

CS = $3776/year

3.4.2. Implementation cost

The estimated implementation cost associated with this recommendation includes three programmable controllers, 15 relays, and the installation labor for the three groups (Eq. (19)).

IC = (3 controllers × $820/controller) + (3 controllers × $65/controller) + (15 relays × $12/relay) + (15 relays × $10/relay)

IC = $2985

The estimated savings of $3776/year will recover the implementation cost of $2985 within 10 months.

3.5. Case study 4: Utilizing existing economizers on air conditioning units

A facility is currently applying the economizer cycle. The cycle is set to draw in about 15% of outside air. This setting is suitable during the summer months. It provides adequate circulation of fresh air without overheating the air supply to the A/C unit. For the winter months (November through March) the dry-bulb temperature is low and ideal for the economizer cycle. Therefore, the dampers should be opened to draw more of the outside air and be utilized to their full capabilities.

The current operating hours for this facility are approximately 0600 to 0300 hours. However, space cooling at the facility occurs 24 h/day for the entire year. Potential savings are based on the assumption that outside air can be used to provide space cooling during the winter months when the temperatures are cooler and the relative humidity is below 50%. This outside air could then be utilized directly without any need for humidification conditioning. C_p, the specific heat of air, is 1009.067 (J/kg K); ρ, the density of air, is 1.20 kg/m^3; H, the number of hours in winter, is 3600 h; and COP, the coefficient of performance, is 2.2. The usage charge is $0.06181/kWh for this facility. The average temperature of outside air during the winter (T_o) is 287 K. The indoor return air (T_r) is 299 K.

3.5.1. Anticipated savings

The weighted average temperature of air supplied to the cooling coil under present conditions results from mixing 15% outside air with 85% indoor return air and is estimated as in Eq. (21).

T_s = (287 K × 0.15) + (299 K × [1 − 0.15])

T_s = 43 K + 254 K

T_s = 297 K

During the audit, the AC unit was estimated to provide cooling for 10 min out of each hour. UF is estimated as:

UF = (10 min)/(60 min) = 0.17.

The energy savings are determined based on Eq. (20).

US = {12 × 9696.44 m^3/h × 1009.067 (J/kg K) × 1.20 kg/m^3 × (297 K − 287 K) × (1/3,600,000) kWh/J × 0.17 × 3600 h/year} /2.4

US = 99,800 kWh/year

The cost savings are calculated as follows (Eq. 22):

CS1 = (99,800 kWh/year) × (0.06181 $/kWh),

CS1 = $6168/year.

The annual energy savings are equal to the usage savings (99,800 kWh/year).

3.5.2. Implementation cost

The existing roof-top air conditioning units are equipped with the necessary dampers to utilize the economizer cycle. Therefore, there will be no implementation cost and the cost savings are immediate. These dampers are

currently drawing 15% outside air. This is an appropriate setting for summer use. The energy cost savings are obtained by opening the dampers to their 100% capacity during the winter months.

4. Conclusion

In the current paper, we have demonstrated that considerable energy and money can be saved in air conditioner and chiller systems by installing higher-efficiency air conditioners, higher-efficiency chillers, duty cycling air conditioning units, and utilizing existing economizers on air conditioning units. The calculation procedures are illustrated with realistic examples. The potential savings and payback periods are evaluated. The approximate energy/demand savings and payback periods of these realistic examples are given as follows:

* The total annual energy saving is determined as 333,369 kWh/year and the payback period is determined as 5 months with the installation of air conditioners that have higher efficiency.

* The annual energy saving is determined as 103,440 kWh/year and the payback period is determined as 3 months with the installation of chillers that have higher efficiency.

* The amount of savings from a reduction in energy demand is 60.39 kW per month and the payback period is 10 months for duty cycling air conditioning units.

* The annual energy saving is determined as 99,800 kWh/year and the payback period is immediate with the utilization of existing economizers on air conditioning units.

We hope that these results will be helpful to manufacturers, engineers, and relevant stakeholders in making investment decisions.

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