AIR-CON SYSTEM EFFICIENCY PRIMER: A SUMMARY

BACKGROUND

Air conditioning is widely used in Singapore with its hot and humid conditions. In our hot and humid climate, the energy consumed by Heating, Ventilation and Air-Conditioning (HVAC) typically comprises up to 50%[1] of total energy consumption in a building. *Figure 1* displays the breakdown.

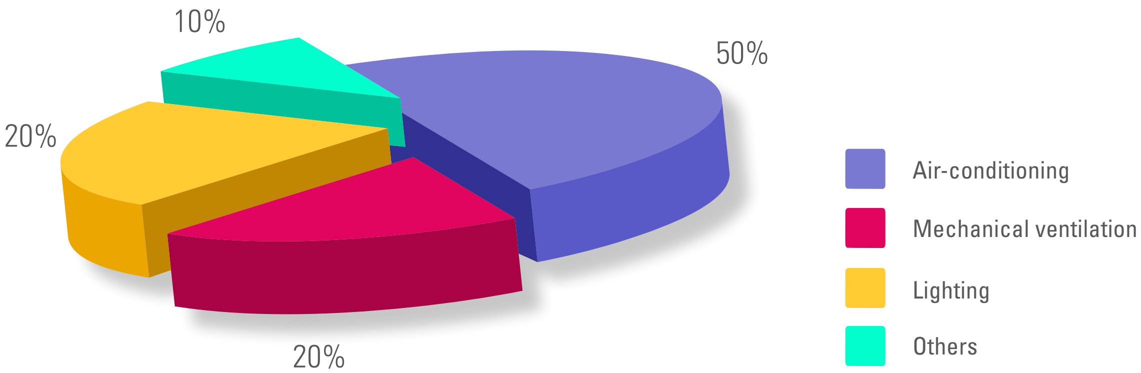

Figure 1: Breakdown of energy consumption within a building[1]

There is potential to improve the overall efficiency of the air-conditioning systems in Singapore. e.g. Many air-conditioned spaces in commercial, hotel and office buildings in Singapore have low temperature settings to compensate for inadequate air distribution in some areas.

DISTRIBUTION OF AIR-CONDITIONING ENERGY CONSUMPTION

The approximate distribution of the energy consumption within air conditioning is 55% for the chiller, 35% for fans, 5% for pumps, and 5% for cooling towers. This highlights the importance of energy efficiency of the chiller in the entire cooling process. *Figure 2* displays the breakdown of air-conditioning energy consumption.[2]

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[1] Singapore's Second National Communication: Under the United Nations Framework Convention on Climate Change (November 2010), NEA.

[2] Roth K. R., Westphalen D. Dieckmann J., Hamilton S.D., Goetzler W.; "Energy Consumption Characteristics of Commercial Building HVAC Systems Volume III: Energy Savings Potential".TIAX LLC Cambridge MA 02140-2390. TIAX Reference No.68370-00

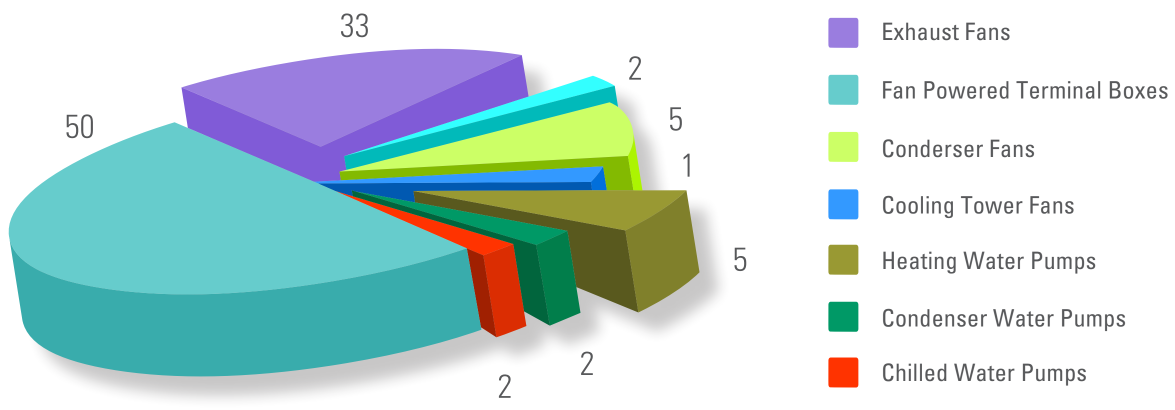

Figure 2: Breakdown of energy consumption of commercial HVAC [2]

UNITARY AND CENTRAL AIR-CONDITIONING SYSTEMS IN SINGAPORE

In Singapore, most air-conditioning systems can be broadly classified into:

a. *Unitary systems*, which are usually simple self-contained air conditioners. These systems cover split room units, packaged units, and more advanced systems capable of varying the refrigerant flow rates (VRV);

b. *Central air-conditioning systems served by chilled water producing plants* (also known as Chillers). Central air-conditioning systems are further sub-classified into:

   (i) All air systems, which circulate air treated in a central location to the conditioned space. Such systems include Constant Air Volume (CAV) systems and Variable Air Volume (VAV) systems.

   (ii) Air-water systems, where chilled water is circulated to fan coils and induction units located in the conditioned space.

For a cooling area above 10,000m^2, water-cooled chillers are more efficient, rather than split-type units commonly used in households. These are typically used in commercial buildings. The authors recommend the possible replacement of existing infrastructure every 10 years to benefit from advances in technology. The improved efficiency could result in energy savings which shorten the payback time to as low as 3 years.

ENERGY AUDITING AND BUILDING STANDARDS IN SINGAPORE

The energy auditing and building standards are as follows:

(i) All large air-conditioned public sector office buildings, as well as polytechnics and ITEs, with central air-conditioning systems and air-conditioned areas greater than 10,000m^2 will be energy audited by FY2011. Infrastructure facilities will also be energy audited by FY2012.

(ii) Large central air-conditioning systems in buildings will be fitted with instrumentation to monitor the coefficient of performance (COP). The air-conditioning systems must be upgraded to achieve a COP[3] of at least 4.7 at the next available opportunity.

(iii) An increase of 1°C in the air-conditioned indoor air temperature could reduce air-conditioning electricity consumption by about 3%. All public agencies are required to ensure that the ambient indoor air temperature of all public sector premises remains no lower than the recommended range of 22.5°C to 25.5°C.

(iv) All new office information and communication technology equipment will meet the latest Energy Star standards, where available, from FY2009 onwards.[4]

PUBLIC SECTOR TAKING THE LEAD

The public sector is taking the lead by using energy and resources more efficiently. As part of this effort, public sector buildings will have to meet energy efficiency targets to reduce energy expenditure. Complementing the Public Sector Taking the Lead initiative, the Building and Construction Authority (BCA) has come up with the 2nd Green Building Masterplan[5] which consists of six strategic thrusts, as shown in *Figure 3*.

Strategic Thrust 1, which is Public Sector Taking The Lead (PSTTL) requires all existing government buildings owned by government agencies, with more than 10,000m^2 air-conditioned floor area to attain the BCA Green Mark GoldPlus standard by 2020. As for new public sector buildings with more than 5,000m^2 air-conditioned floor area, including buildings whose development costs are fully or partly funded by government agencies (e.g. new universities and hospitals), these buildings will have to achieve the Green Mark Platinum rating.

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[3] The COP, achieved by the system in which the compressor is connected to operate, is the ratio of the rate of heat removal from the space to be cooled (kW cooling) to the energy input rate required by the system (kW in).

[4] www.e2singapore.com

[5] 2nd Green Building Masterplan (2009), BCA. www.bca.gov.sg/GreenMark/others/gbmp2.pdf

Figure 3: 2nd Green Building Masterplan Strategic Thrusts [5]

Beyond improving building energy efficiency, all agencies are also encouraged to adopt environmentally sustainable practices that are cost beneficial, such as participating in the Water Efficient Building and Eco-Office rating frameworks developed by the Public Utilities Board (PUB) and the Singapore Environment Council respectively, and implementing recycling programmes.

Through this PSTTL initiative, the public sector aims to demonstrate the associated environmental and economic benefits and set an example for the private sector. Public agencies are also encouraged to finance and implement their energy efficiency improvements through Performance Contracting.[4] More information on performance contracting is given in *Appendix A*.

The Ministry of Environment and Water Resources (MEWR) and National Environmental Agency (NEA) jointly launched the Energy Efficiency Improvement Assistance Scheme (EASe) in 2005. Under this scheme, owners and operators of facilities in the manufacturing sector can obtain 50% subsidies for the engagement of energy services companies (ESCOs) to conduct energy audits on a voluntary basis. This scheme has since been extended to other commercial users and households. In addition, for large energy consumers,[6] an energy manager has to oversee the usage of the organisation to ensure energy efficiency measures are put in place.

[6] Large consumers are mainly industrial (and other commercial) users whose monthly consumption exceeds 10,000 kWh.

Separately, the BCA has rolled out Green Mark Incentive Schemes for new buildings as well as existing buildings. Under the new buildings incentive scheme, buildings which achieve the higher Green Mark ratings, namely the GoldPlus and Platinum rating, will be given bonus Gross Floor Area (GFA) of 1% and 2% respectively. For existing buildings, a $100 million incentive comprising of 2 components, the cash incentive as well as the health check scheme, has been rolled out to encourage existing buildings to go Green. Existing buildings which meet the requirements can be given cash incentives of up to $1.5 million for the co-funding of energy efficient retrofits.

In the latest Green Mark Version 4 for new buildings (updated in December 2010),[7] minimum standards for instrumentations monitoring the central chilled-water plant efficiency as well as the verification of the central chilled-water plant efficiencies have also been incorporated. The minimum air-conditioning system efficiencies for Green Mark Certification have also been raised and are shown in *Figure 4*. Higher rating categories (Gold Plus and Platinum) have higher efficiency requirements (lower kW/RT).

Green Mark Rating	Type of Air-Conditioning System	Peak Building Cooling Load	
		< 500 RT	≥ 500 RT
		Efficiency (kW/RT)	
Certified	Water-Cooled Chilled-Water Plant	0.80	0.70
Certified	Air-Cooled Chilled-Water Plant or Unitary Air-Conditioners	0.90	0.80

Figure 4: Minimum air-conditioning system efficiencies for Green Mark Certification[7]

AN EXAMPLE OF SAVINGS FROM IMPROVING THE EFFICIENCY OF CHILLER SYSTEMS

The Shangri-La Hotel in Singapore had upgraded its air-conditioning plants. It had operated an air-conditioning system of 3,252 refrigeration tonnes (RT) capacity at an average efficiency of 1.22 kW per RT. It has since upgraded the air-conditioning system with better equipment. The current installed capacity is 2,600 RT with an average system efficiency of 0.68 kW per RT. The project has resulted in a saving of 14,400 kWh of electricity per day.[8]

[7] www.bca.gov.sg/GreenMark/others/gm_nonresi_v4.pdf

[8] Singapore's First National Communication: Under the United Nations Framework Convention on Climate Change (2000), NEA.

EFFICIENCY AND SAVINGS: UNITARY SYSTEMS

Besides commercial buildings, the average household can also save money by investing in a more efficient air-conditioning unit. This is indicated by a higher number of energy efficiency "ticks" for the unit. A comparison of the cost savings from changing to a 4-tick unit over a 1-tick unit is given in *Figure 5*. The life-cycle cost is much lower, almost half, due to cost savings in electricity consumption. This is true for the whole range of 1- to 4-tick air-conditioners.[9] *(See Figure 6)*

No of ticks	1-tick	4-tick
Purchase price	$1,590	$2,180
Lifespan energy cost	$10,690	$5,470
Total life cycle cost	$12,280	$7,650

Figure 5: Comparison of 1 tick and 4 tick air-conditioner costs[9]

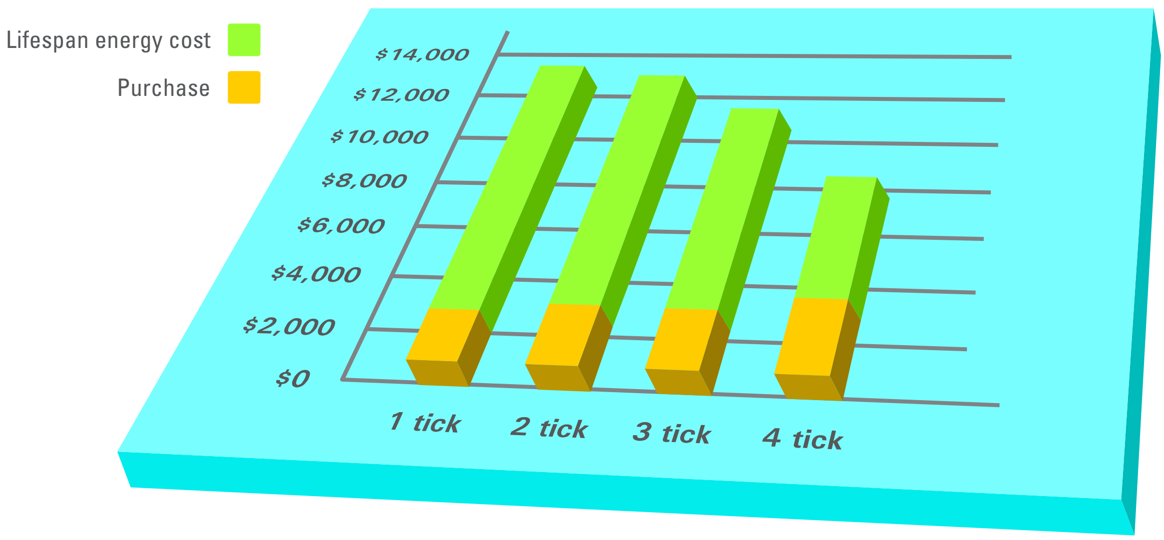

Figure 6: Comparison of capital expenditure and operating expenditure[9]

[9] Energy Challenge Brochure (May 2010), NEA.

Such split incentives in cost are most apparent in commercial settings where the capital expenditure is borne by one party and the operating expenditure is borne by another. The chiller units are often oversized by the developer to ensure that occupants do not complain that the space temperature is too high. Also, the developer does not have to bear the long-term operating cost, which is usually paid by the tenants/users of the building. Accurate sizing of chiller units for central air-conditioning would help to alleviate the problem of over-cooling in commercial buildings, and lead to sizable cost and energy savings.

HUMAN THERMAL COMFORT

The American Society of Heating, Refrigerating and Air-conditioning Engineers, Inc. (ASHRAE) defines Human Thermal Comfort as the state of mind that expresses satisfaction with the surrounding environment. The purpose of air-conditioning is to maintain thermal comfort conditions for occupants in a building. It must be stressed that thermal comfort is not dependent upon temperature alone and includes other factors such as humidity and vapour pressure.

ASHRAE has developed an internationally accepted standard to describe comfort requirements in buildings.[10] This Standard allows the comfort charts to be applied to spaces where the occupants have specified physical activity levels and where clothing is worn that provides specific level of thermal insulation. *(See Figure 7)*

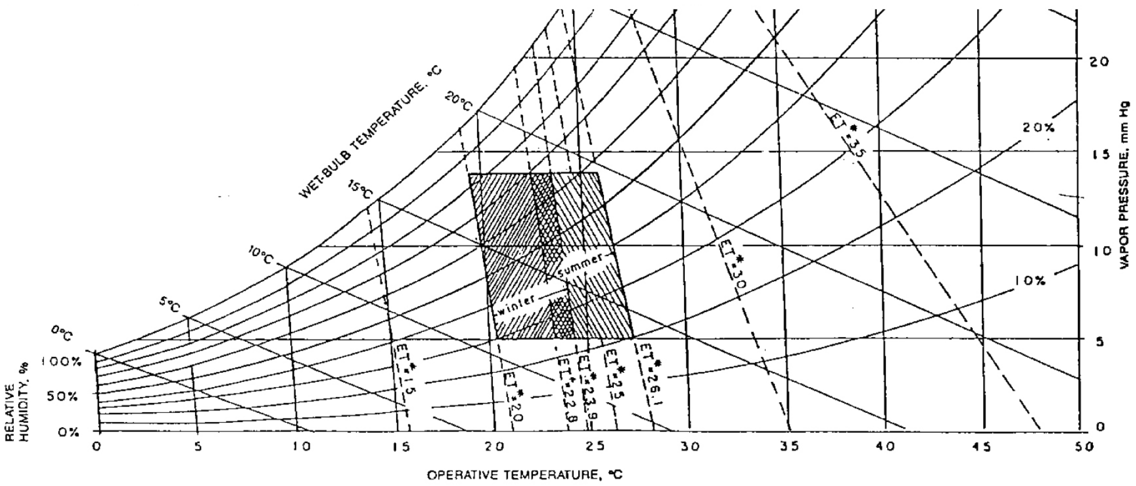

Figure 7: ASHRAE thermal comfort chart[10]

However, as Singapore does not have four seasons in a year, the ASHRAE recommendations have to be adapted to suit our unique circumstances. Recommended indoor conditions appropriate for our climatic conditions are specified in Singapore Standard SS553:2010. The design temperature is between 23 to 25°C, with relative humidity not exceeding 65%.

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[10] ASHRAE Standard 55-2004 Thermal Environmental Conditions for Human Occupancy.

OVERVIEW OF HVAC SYSTEM

A HVAC system in buildings may be described in general terms as a system for providing the right conditions inside the building for the thermal comfort of the occupants or the operating requirements of equipment and processes. It will usually involve the addition or removal of heat or moisture between the building interior and the exterior environment. In Singapore, because of our climatic conditions, air-conditioning primarily involves cooling and dehumidification processes.

Figure 8 shows a schematic of a typical building HVAC system, divided into five heat transfer loops[11]:

i. Indoor air loop includes fans, cooling coils, terminal units, dampers, ducts, and controls. The air in the conditioned space is driven by fans through cooling coils and then distributed to terminal units. Dampers are used to control airflows to terminal units and fans are used to maintain a given air pressure in ducts. The cooling and ventilation loads are transferred from the conditioned space to chilled water.
ii. Chilled water loop includes pipes, pumps, cooling coils, chiller evaporators, valves, and controls. The chilled water in pipes is driven by pumps to circulate between cooling coils and chiller evaporators. Valves are used to control the water flow to cooling coils. The heat is transferred from air handling units (AHUs) to chiller evaporators.
iii. Refrigerant loop includes evaporators, compressors, condensers, expansion valves and controls. The refrigerant absorbs heat in chiller evaporators by changing phase from liquid to gas. The working of compressors makes the refrigerant a high pressure and high temperature state. The refrigerant with high temperature is cooled in chiller condensers. The high pressure refrigerant in gas is released by expansion valves back to evaporators again with phase change. The heat is transferred from chiller evaporators to chiller condensers.
iv. Condenser water loop includes cooling towers, chiller condensers, pumps and controls. The condenser water in chillers is delivered to cooling towers by pumps. The heat is transferred from chiller condensers to cooling towers.
v. Outdoor air loop includes fans, cooling towers, and controls. The outdoor air is driven by fans to go through cooling towers and to exchange heat with condenser water. The heat is transferred from cooling towers to ambient environment.

A refrigeration machine is used to maintain the evaporator coil at its low temperature by circulating a refrigerant through the coil. The refrigerant vapour at the evaporator coil is pumped to a higher pressure by a mechanical compressor where it is condensed to a liquid at another set of condenser coils. The high pressure liquid refrigerant is then allowed to expand in the evaporator coil again to complete the cycle. The heat absorbed at the evaporator coil is pumped by the refrigeration machine and rejected to the ambient at the condenser coils. Mechanical work is needed to drive the compressor. The amount of effort needed to drive the compressor is very dependent on the temperature difference at the evaporator and the condenser. The greater the difference in temperature, the greater is the effort.

[11] Lu L., Cai W., Chai Y. S., Xie L; "Global optimisation for overall HVAC systems-Part I problem, formulation and analysis". Energy Conversion and Management, 46 (2005) p.999-1014.

This explains *why in a simple air-conditioner, a higher thermostat set-point temperature saves energy. Similarly, a reduction in the condensing temperature saves energy.*

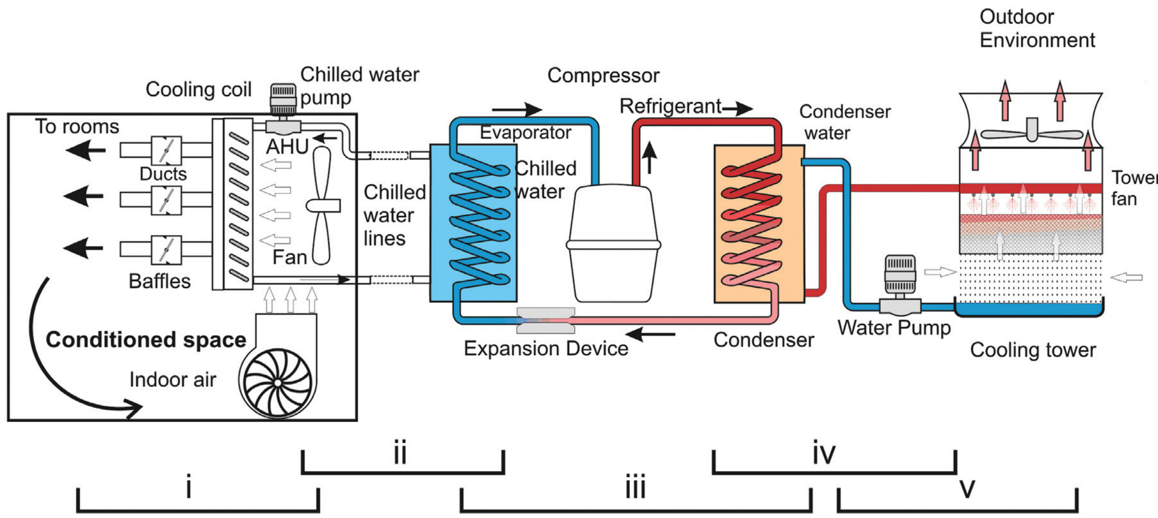

Figure 8: The schematic of a typical building HVAC system

OPPORTUNITIES TO IMPROVE ENERGY EFFICIENCY

(A) Use of Desiccants To Improve Energy Efficiency of Chillers

Imported air conditioners are designed to work in both summer and winter conditions. Singapore is a tropical country with an average annual ambient relative humidity of 85%. Conventional air-conditioning in hot-humid climates consists of cooling and dehumidification of the air in the conditioned space to maintain human thermal comfort. This is achieved by flowing moist air over a finned cooling coil whose surface is maintained below the moist air dew point temperature. The air gets cooled and dehumidified.

Since energy consumed by the chiller depends very much upon the surface temperature of the cooling coil, the energy consumed by the chiller would be reduced significantly by raising this surface temperature. Thus, if the removal of moisture in the air[12] *can be handled by other means apart from condensation, e.g. by the use of desiccant, the cooling energy*[13] *can be reduced.* Other forms of energy are still required to regenerate the desiccant (waste heat from industrial processes, solar thermal, etc.), but there can still be an overall reduction in energy consumed by this process of separately cooling by refrigeration and dehumidification by desiccant. Some newer technologies that may reduce the energy needs of air-conditioning are given in *Appendix B*.

[12] The energy removed from the air is considered the sensible load.

[13] The energy in the moisture removed forms the latent load.

(B) Improvements Needed to Existing Control Systems

The adoption of advanced reliable and cost effective control systems aims to optimise the running of the HVAC system. The current Building Automation Systems (BAS) and Energy Management Systems (EMS) do provide certain procedures to improve energy efficiencies and human comfort for building HVAC processes. However, the *authors assess that the very large amount of data involved places huge burdens on the communication network and the processing capacities of the systems. In order to relieve these burdens, they treat many variables as constants and each of these function loops operates independently.* This kind of operation will require more energy than actually required for the circulation of refrigerant, air, or water to maintain the specified indoor environment. Wireless technology as well as improved communications protocols, efficient sensor nodes and sensor network platform should be developed. With the deployed sensor nodes, information regarding various outdoor and indoor environmental conditions can be obtained.

(C) Optimisation of Air Distribution

The parasitic energy for transferring heat from the conditioned space to the cooling equipment is a significant part of the cooling system energy consumption. Various schemes are available to minimise energy use in the distribution system, such as a Dedicated Outdoor Air System (DOAS) which separates the fresh air requirements from the re-circulated space air-conditioned air, and the use of chilled beams and radiant panels which achieve energy savings through a reduction of fan energy for air circulation and the use of radiant cooling, albeit requiring more chilled water distribution.   Innovative air distribution systems can also supply just the right amount of fresh air locally to meet the physiological and air quality demands. *(See Appendix B)* *The authors assess that energy use by the air distribution in the HVAC system can be minimised through an understanding of the local needs and optimising the manner in which the cooling energy is supplied through various innovative schemes.*

LOCAL RESEARCH TESTBEDS

There are local research testbeds, which focus on some areas of air-conditioning efficiency, within both NTU and NUS. *In particular, the Single Coil Twin Fan System by Enhanced Air Quality Pte Ltd (NUS) has been testbedded in the Zero Energy Building at the BCA Academy. Examples of research testbeds in Singapore are described at Appendix C.*

AREAS OF R&D FOR SINGAPORE

Although Singapore is not a manufacturer of HVAC systems, the authors feel that there is a case for the local development of HVAC technologies suited for local hot and humid conditions. *The authors recommend that areas of R&D for air-conditioning efficiency for Singapore should include:*

a. *Desiccant cooling technologies, such as sorption dehumidification*[14] *and desiccant materials;*
b. *Control systems, such as sensor network platforms; and*
c. *Innovative air distribution schemes*

Separately, the mass implementation of best practices would include avoid oversizing of chillers, thus reducing excessive energy consumption for cooling of buildings. Improvement in the layout and position of thermostats to ensure proper measurement and verification according to best-in-class performance benchmarks would also improve the efficiency of systems in existing buildings. These can be done even using the current state of technologies, while better solutions are being developed.

CO_2 REDUCTION ENABLED BY IMPROVING AIRCON SYSTEM EFFICIENCY

The use of electricity generated by fossil fuel sources is a source of CO_2 emissions. Reduction of energy used through improved air conditioning system efficiency can reduce emissions significantly, as air-conditioning is a main component the energy consumption of buildings.

[14] Sorption dehumidification is heat driven and utilises the difference in the vapour pressure between process air and desiccants to realise humidity control. Sorption dehumidification can be further classified into two categories, namely, adsorption dehumidification (solid desiccant) and absorption dehumidification (liquid desiccant). When the desiccant material is cold and dry, its vapour pressure is lower than process air and moisture transfer from the air to the desiccant material takes place. Consequently, process air is dehumidified

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APPENDIX A

PERFORMANCE CONTRACTING

Performance contracting is an arrangement under which an Energy Services Company (ESCO) is engaged to review the energy consumption of a building or facility and to identify measures that will achieve energy savings. The level of savings is guaranteed by the ESCO. The ESCO therefore assumes the technical risks of implementing the measures.

A Performance Contract is a contract with an Energy Services Company (ESCO) to:

a. Review the energy consumption of a building or facility
b. Identify measures that will achieve energy savings
c. Implement the measures and guarantee the savings

There are two general models of performance contracting:

a. Shared savings model: The ESCO will bear the cost of implementing the energy efficiency projects. The ESCO then recoups the implementation cost from the company by sharing a fixed proportion of the energy savings proceeds with the company over a specified period of time.
b. Guaranteed savings model: The implementation costs are borne by the company but the ESCO provides a guarantee that the energy efficiency projects will achieve the promised energy savings. Any shortfall in savings will therefore be made up by the ESCO.

HVAC: UPCOMING TECHNOLOGIES

Dedicated Outdoor Air System (DOAS)

A Dedicated Outdoor Air System (DOAS) separates outdoor make-up air-conditioning from re-circulated space air conditioning. DOAS deals with ambient humidity directly at the source. This approach has energy saving potential because it provides only the amount of outside air necessary to maintain the Indoor Air Quality (IAQ) levels and also by recovering the cool energy from the exhaust air to pre-cool the make-up air. The building interior load is mostly sensible cooling.

Dryer, conditioned outside air allows sensible cooling of re-circulated space air using a higher chilled water temperature. This results in less energy being needed in the refrigeration system to achieve cooling. Also, a superior humidity control is achievable.

Radiant panel cooling by chilled beams or chilled ceilings

Conventional variable air volume (VAV) systems for large commercial buildings use a large fraction of their energy just to distribute energy in air. Pumping air is much less efficient than pumping water.

Coupling of space sensible cooling with DOAS is possible through the use of radiant cooling by chilled beams or chilled ceilings. Chilled beams and chilled ceiling systems use radiant ceiling cooling panels and energy savings are achieved from the reduction of fan energy for thermal distribution parasitic power.

DOAS reduces energy use in three ways:

i. It optimises ventilation air supply to meet IAQ requirements,
ii. allows pre-cooling of make-up air by space exhaust air heat exchange, and
iii. allows use of higher chilled water temperature for sensible cooling of interior loads, thus improving chiller COP. [15]

[15] The Coefficient of Performance (COP), is the ratio of the rate of heat removal from the space to be cooled (kW cooling) to the energy input rate required by the system (kW in). Industry practice usually specifies the kW power input required per ton of refrigeration (kW/RT, 1RT = 3.516 kW cooling), which has an inverse relationship with COP.

Innovative air distribution systems

Traditional ventilation systems distribute air based on the well-mixed principle for indoor pollutant dilution. Recent developments in air distribution systems proposed the idea of supplying the fresh air locally to the human breathing zone only to achieve high efficiency of air pollutant dilution. Some of these innovative air distribution systems include under-floor ventilation, displacement ventilation and the previously mentioned personalised ventilation. The high air distribution effectiveness will not only improve indoor air quality but also save air-conditioning energy since less fresh air is needed for dilution. In the US, provisions are given in the latest ventilation standards to ease the fresh air supply rate prescriptive requirements for innovative air distribution systems. e.g. ASHRAE Standard 62-2007 incorporates the concept of "Zone Air Distribution Effectiveness", which allows innovative air distributions systems having zone air distribution effectiveness larger than 1.0 to lower the fresh air supply rate accordingly.

Special Air-Conditioning System Designs

District Cooling System (DCS)

A DCS distributes chilled water from a central source to multiple buildings through a network of underground pipes. The cooling (chillers) and heat rejection (cooling towers) are provided at a central plant location, thus eliminating the need for separate systems in individual buildings. There are obvious savings in centralising the space and maintenance requirements, but this is balanced by the need to construct and maintain the distribution network. If there is good diversity in the cooling profile of the various buildings (i.e. the peak loads do not occur at the same time), coupled with centralising the back-up capacity requirements, there can be substantial savings in the total cooling equipment capacity. A DCS operator will also usually invest in a *thermal storage facility*[16] which can enable it to further benefit from peak load shaving, or generating its cooling requirements during off-peak hours at cheaper rates. But from an energy perspective, a DCS will have to address the additional pumping requirements of the distribution network and the need to provide a slightly lower chilled water supply temperature to cater for inevitable losses in the piping. In short, a site-specific techno-economic optimisation needs to be carried out to determine if a DCS will be beneficial from the point of view of energy use, space use, cost and business considerations, before a decision should be made. Singapore currently has four major DCS sites. These cater to sites with relatively different nature of operations: a high-tech industrial park with 24-hour operations, a research hub, a business park and a commercial/financial centre. A study of the energy performance from these diverse operations will yield very good information on the applicability of DCS to potential sites in Singapore.

[16] Thermal energy storage (TES) is a concept whereby energy is stored, when available, to be used when needed. This currently consists of a number of technologies that store thermal energy in energy storage reservoirs for later use. These are normally adopted to balance energy demand between day time and night time. The thermal reservoir may be maintained at a temperature above (hotter) or below (colder) that of the ambient environment. The principal application today is the production of ice, chilled water, which is then used to cool environments during the day. High temperature salts can be employed to store thermal energy which can be transformed to electrical energy (through the use of steam) when demand is high. Technologies adopting TES are described in detail in the Energy Storage Technology Primer.

APPENDIX C

LOCAL RESEARCH TESTBEDS

Local areas of research testbedding that focus on some of these areas exist within both NTU and NUS, namely:

- Model based dynamic optimisation for HVAC processes (NTU),
- Ejector refrigeration cycle (NTU),
- Double refrigeration cycles (NTU),
- Liquid desiccant Dehumidification (NTU),
- Single Coil Twin Fan System. Enhanced Air Quality Pte Ltd (NUS), and
- Adsorption Refrigeration Cycles (NUS).