CH_2 Energy Harvesting Systems: Economic Use and Efficiency

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ABSTRACT

This paper looks at the City of Melbourne's new office development CH_2 as a case study of world class energy performance. In particular, the integrated design of conventionally independent systems has led to the potential to deliver significant savings to the Council and to deliver better environmental conditions to building occupants that in turn may contribute to satisfaction, well-being and productivity. It is concluded that this project has the potential to be an iconic example of effective implementation of ESD (environmental sustainable design) principles and therefore act as a demonstration project to others. Energy efficiency of more than 50% of current benchmarks for Melbourne is effected. Energy harvesting is defined as arising from squander, waste and nature, which is a new concept introduced in this paper to better describe the design decision process.

Keywords: energy efficiency, harvesting, thermal comfort.

INTRODUCTION

Environmental depletion, global warming and the consequential climate changes are key environmental issues for today's generation. These result from excessive greenhouse gas emissions from burning of fossil fuel since the industrial revolution (Lawson, 1996; Steele, 1997). The time-lag between actions and changes in outlook in environmental systems determine that decisions made by us now will affect subsequent generations and the future of our environment.

Australia has the highest greenhouse gas emissions per capita in the world (SEAV, 2001). Commercial buildings are large energy consumers, as energy is the lifeblood of contemporary office buildings. No office building can function properly without energy supply. Energy intensity is increasing and is also making a significant contribution to peaks in electricity demand, particularly with the increased reliance on air conditioning (ABARE, 1999). According to PCA (2001), commercial buildings in Australia generate more than 35 million tonnes of CO_2 (carbon dioxide) a year, and if no action is taken to reduce growth, that figure is projected to double within a decade.

Harvesting energy in office buildings provides a way of meeting increasing energy needs without adding to greenhouse gas emissions. This focus recognizes that building design and systems integration are key strategies for capturing significant greenhouse gas emission reductions from office buildings over the longer term, although other abatement measures may in some cases be more attractive in the short term.

While the majority of energy consumption occurs in existing buildings, new and refurbished buildings present major opportunities to leverage capital investment and demonstrate new and innovative approaches to building design and construction. To be a credible leader in energy management within the community, the City of Melbourne (CoM) must first ensure that their own energy consumption is as efficient and effective as possible. With great foresight, the CoM is committed to pursue an active role in reducing greenhouse gas emissions.

The CH_2 proposal therefore had to meet at least a 5 star energy level and the energy targets set out under the Energy Management Strategy and accompanying Energy Policy to guide corporate change (CoM, 2004).

The CH_2 project is new office accommodation currently being constructed, and is anticipated:

- to demonstrate the Council's commitment to effective greenhouse action and provide strong leadership to the community;
- to reduce greenhouse gas emissions arising from the Council's operations;
- to drive cultural change across all government agencies with respect to improvements in energy management and the integration of environmental considerations; and
- to display energy reduction targets and realise CO_2 savings that can be achieved through cost-effective action, without compromising productivity and working conditions, and assist in holding down electricity costs within the Council budget sector over the medium term.

This study documents the energy harvesting systems within CH_2 and assesses these with respect to international best practice. Inclusive in this study is an assessment of the current state of related industries within Australia and identification of areas for improvement in meeting the needs of the expanding ESD industry.

This paper aims to offer a more integrated approach and to suggest some solutions based on research into current good practice. First, an appraisal on energy use in the current office building stock in Australia is given. Second, building energy benchmarking schemes are reviewed. Third, the potential area for energy harvesting in office buildings is defined. Fourth, a brief description on energy harvesting systems in CH_2 is provided followed by discussions on the successfulness on the system integration in CH_2. Finally, a conclusion is offered.

HOW ENERGY IS USED IN AUSTRALIAN OFFICE BUILDINGS

Energy is not used for its own sake. It is one of many inputs to a system that produces useful and valuable outputs. In office buildings, energy is used to create a comfortable and healthy working environment, as well as powering equipment which are required to get work done. A typical break down of relative energy consumed by commercial buildings in Australia is shown in Figure 1. Greenhouse gas emissions are used here to indicate the amount of primary energy used as opposed to the convention of measuring delivered energy. This approach takes into account the efficiency of energy production which can truly reflect the real energy resources consumed by buildings.

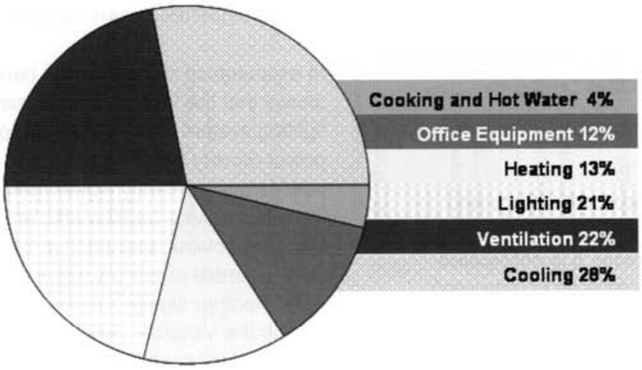

Figure 1: Commercial building greenhouse gas emissions (EMET, 1999)

It is found that the majority of energy consumed is dedicated to the provision of thermal comfort, including heating, cooling and ventilation services, which account for 63% of total greenhouse gas emissions in Australian commercial buildings. Ventilation systems are also responsible for removing contaminants in the space and providing fresh air to the building occupants which is essential for their health and well-being. The third largest single consumer is lighting systems which is required for maintaining sufficient illumination in the office for occupants to perform their work and for safety and security purposes. On the other hand, energy is also required to power all the office equipment including computers, printers and photocopier, to name but a few. In contemporary offices, almost every workstation is equipped with a desktop computer. These office machines account for 12% of overall greenhouse gas emissions in Australian commercial buildings. The ultimate aim of all the above energy consumption is to improve the productivity of building occupants.

The average annual energy consumption per unit floor area of Victorian office buildings is compared against overseas data in Figure 2. The results indicate that, on average, office buildings in Victoria have the second lowest level of energy consumption in the selected countries in the Asia Pacific region. They also consume less than half of the energy used by their counterparts in the United Kingdom and United States. It is worth noting that these data are not normalized for climatic differences. Therefore, direct interpretation on data to conclude that office buildings in Victoria are more energy efficient than those in other countries is not appropriate, as climate in Victoria is milder when compared to either the warm and humid tropical climate of Thailand and Singapore or the colder climate of the UK and certain parts of the US.

Figure 2: Comparison of average unit consumption of energy for office buildings in Australia with overseas data

Source: [1] PCA (1997), [2] CDM (2002), [3] Action Energy (2003),
[4] Rating Energy Performance: Office Buildings, http://eber.ed.ornl.gov/benchmark/off.htm

BUILDING ENERGY BENCHMARKS IN AUSTRALIA AND OVERSEAS

Building energy benchmarks is a set of representative values on building energy consumption against which users can compare a building's actual performance.

These benchmarks are designed to achieve two main objectives:

- To allow users to benchmark their building energy consumption levels with the respective sector that they belong to.
- Help energy targets for energy consumption by designers or building management professionals.

These benchmarks are based on surveys of buildings and evaluation of the performance of systems considered to reflect good practice in the field at the time. It is anticipated that the establishment of benchmarks can lead to improving the performance of average buildings to the level of good practice which eventually will lead to significant energy savings. Benchmarks are valuable tools for both government and the private sector to manage energy usage with respect to the climate and specific needs for respective building typology. In the event that the energy consumption of the building falls outside prescribed limits, the design or building management team can seek advice for improving energy performance.

There are two major types of building energy benchmarks:

- simple benchmarks with only overall annual energy consumption per unit floor area or annual greenhouse gas emission per unit floor area.
- Detailed benchmarks with sub-benchmarks on most of the essential services, including lighting, cooling, heating, ventilation, equipment and vertical transportation.

Comparison with simple benchmarks of annual energy use per square metre of floor area will permit the standard of energy efficiency to be assessed and enable remedial action to be taken. More detailed benchmarks can help pinpoint problem areas within a building.

A number of local and overseas energy benchmarks are summarized in Table 1. Some of these benchmarks come with energy efficient guidelines that address issues of good management, as well as proposing energy targets achievable by application of good practice. Once again, the benchmark for Melbourne offices has the lowest overall energy consumption level amongst the four countries/regions listed, and reflects the phenomenon observed in the average energy consumption of various countries shown earlier in Figure 2.

In examination of the detailed benchmarks of individual services shows that the Victorian benchmarks are more relaxed on the lighting system when compared to other countries. Both the lighting power density (W/m^2) and lighting energy consumption ($kWh/m^2/year$) are significantly higher than the other benchmarks. Most of the other service benchmarks are comparable with figures for the UK. One obvious exception is the heating energy requirement, as the climate of the UK has a higher number of heating degree days. Another significant observation from Table 1 is that even though the Victorian benchmarks only have half to three quarters of the energy consumption of the UK benchmark, and the figures for greenhouse gas emissions are one and a half to two times that of the UK benchmark. This leads to a greater concern on the selection of energy sources in Victorian office buildings and further stresses the need to reduce energy consumption.

The BOMA 1994 design target is included in Table 1 in order to illustrate growth in energy consumption in cooling, ventilation and office equipment. The improvement in efficiency of building services and office equipment should lead to a reduction in energy consumption of office buildings and hence lower the benchmarks. These changes, contrary to the latest benchmarks can gradually improve the energy performance of buildings over time by raising the energy efficiency target. The reality is that the density of office space has become higher and results in a higher ventilation requirement. Another reason is that newer more powerful desktop computers generate more heat and explain the increased energy consumption of office equipment and the cooling load which is required to remove the extra heat given out by the extra occupants and equipment.

	Overall energy consumption ($kWh/m^2/year$)	Overall Co2 emissions ($KgCo2/m^2/year$)	Lighting Power density (W/m^2)	Lighting energy consumption ($kWh/m^2/year$)	Lighting energy consumption ($kWh/m^2/year$)	Lighting energy consumption ($kWh/m^2/year$)	Ventilation and Pump energy consumption ($kWh/m^2/year$)	Office equipment (W/m^2)	Office equipment ($kWh/m^2/year$)
Australia									
BOMA 1994 New Building Design Target (Melbourne)	118	114	14	36	10	37	14	5	12
PCA 2001 Good Practice Benchmark (Melbourne)	186	196	15	39	17.5	47	28	n.a.	24
PCA 2001 New Building Design Target (Melbourne)	133	142	11	31	13	31	22	n.a.	15
ABGRS 5 stars		170							
UK [1]									
Energy Consumption Guide 19- Good Practice	225	85	12	27	14	97	30	14	23
Germany [2]									
Guidelines for sustainable building			10					25	
US[3] CBCES	252		14*						
Hong Kong[4] Best Practice	226								

*ASHRAE 90.1-2001

Table 1: Summary of Local and Overseas Building Energy Benchmarks

[1] Energy consumption guide, www.actionenergy.org.uk

[2] FOBRP (2001), Guideline for Sustainable Building, Federal Office for Building and Regional Planning, Germany

[3] CBCES (2000), Energy Information Administration: 1999 Commercial Buildings Energy Consumption Survey

[4] CDM (2002), Consultancy Study on the Development of Energy Consumption Indicators and Benchmarks for Selected Energy-consuming Groups in Hong Kong, http://www.emsd.gov.hk/emsd/e_download/pee/esab.pdf

ESD OFFICE BUILDINGS AND BENCHMARKS

The predicted energy consumption of three ESD office buildings, including CH_2, are shown in Table 2. Only ESD buildings in Melbourne have been included which eliminates the effect of climatic difference, hence allowing direct comparison of figures.

It is worth noting that there are more ESD labelled buildings in Victoria (SEAV, 2000); however, figures on detailed energy consumption targets are not available. To the author's knowledge, there is no published data on measured energy performance for any ESD labelled building in Victoria.

	Overall energy consumption (kWh/m²/year)	Overall CO2 emissions (KgCO2/m²/year)	Lighting Power density (W/m²)	Lighting energy consumption (kWh/m²/year)	Lighting energy consumption (kWh/m²/year)	Lighting energy consumption (kWh/m²/year)	Ventilation and Pump energy consumption (kWh/m²/year)	Office equipment (W/m²)	Office equipment (kWh/m²/year)
Building T[1] - Target	100	n.a.	n.a.	25.00	13.3	6.7	n.a.	n.a.	12.5
60 L[2] - Prediction	34	n.a.	7.0	6.0	7.0	13.0	n.a.	5.0	6.0
CH_2[3] - Prediction	58.6	68.6	8.0	5.5	1.7	12.6	8.0	4.3	11.5

Table 2: Predicted Energy Performance of Selected ESD buildings and the CH_2 Project

[1] SEAV (2000), Energy smart building design, SEAV, Melbourne
[2] 60L (2004), http://www.60lgreenbuilding.com, Australia Conservation Foundation
[3] ACE (2004), report: VCML250280\0\2\AR30509

It is observed that all three buildings have significant reduction in predicted energy consumption over the building energy benchmarks in Table 1. CH_2 has the lowest energy consumption in most of the categories except overall energy consumption and office equipment. The less impressive result in the office equipment category results from a higher occupant density when compared to 60L. The energy harvesting systems in CH_2, which will be examined in the next section, should perform well. One of the most significant savings is in cooling energy consumption. CH_2 is predicted to consume only 17% of the strictest energy benchmark and 24% of the best performing counterpart in Melbourne. The lighting performance is just 18% of the toughest benchmark. CH_2 with a highly disadvantaged deep floor plan has predicted lighting energy consumption lower than that of 60L.

ENERGY HARVESTING IN THE CH_2 BUILDING

Energy harvesting systems is defined in this paper as a system which converts energy potential available on site into energy services that are required for the building to function. This is different from the prevailing concept of energy production systems which convert energy available from nature directly into electricity or usable heat. It is important to realize that building occupants need energy services rather than energy supply. By the same token, energy harvesting systems do not necessarily harvest energy in the form of electricity. Under this definition, any system that can contribute to the provision of services without extra energy input can also be seen as an energy harvesting system as the surplus from reduction in energy consumption is equal to the extra energy production for other uses.

This service-based paradigm on energy harvesting systems helps to clarify the nature of the services that require energy inputs, and facilitates alternative methods of achieving the required outcome. The correct definition of a service requirement is an important step towards identification of the potential for energy efficiency improvement, as it allows unconventional thinking. For example, building occupants need a thermally comfortable environment which is not necessarily delivered by air conditioning systems. In days when outdoor conditions are pleasant, opening windows can provide the same if not higher level of comfort without any expense of energy.

Energy harvesting can be divided into three main categories:

- Harvesting from 'squander' - this is aimed to reduce energy consumption by improving efficiency and eliminating over supply of services.
- Harvesting from waste - this is aimed to recover energy which would otherwise be dissipated to the environment as waste.
- Harvesting from nature - this is aimed to collect energy or the service from the ambient environment and deliver it to the building occupant.

Under these three titles, the choices made in the selection of technologies and energy sources are investigated, and interpretation on the nature of useful services is made. This highlights the many choices that are available, each with its own unique energy and environmental impacts. The design of CH_2 incorporated a number of energy harvesting features (AEC, 2003a). These features are grouped into the above categories of opportunities which, in turn, enable systems to be analysed together along with the influence on energy consumption of the building. An overview of the energy harvesting systems proposed for the CH_2 is presented below. This is followed by a review of the individual components used for energy harvesting systems and their expected performance in the Melbourne climate.

The CH_2 building is located in Melbourne (latitude 37°49'S and longitude 142°30'E), the capital of the State of Victoria in south eastern part of Australia. The climate is classified as temperate. However, the weather in Melbourne is highly inconsistent, and is sometimes described as 'four seasons in one day'.

Figure 3 shows in the reference weather year, there are 414 occupancy hours (08:00 – 18:00) that have outdoor air temperature above 24°C and 3234 occupancy hours below 21°C.

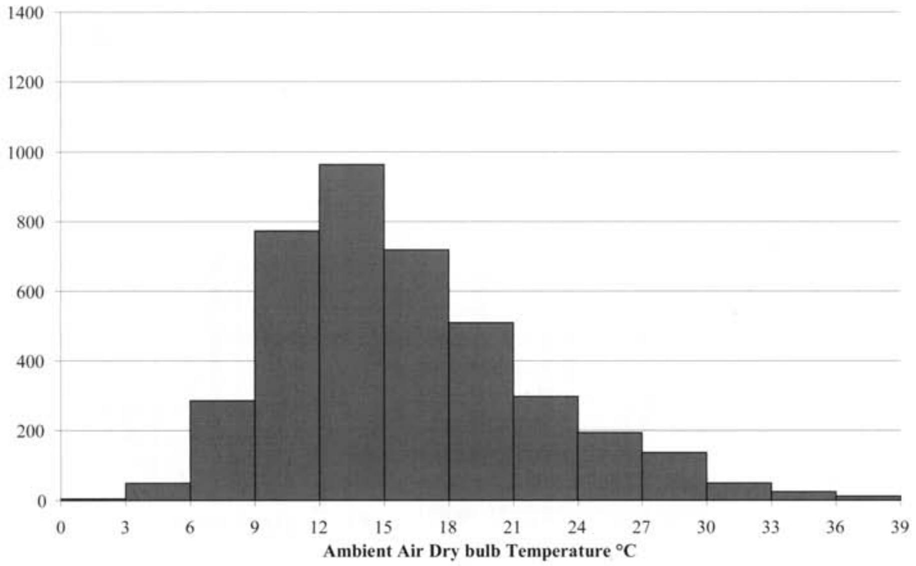

Figure 3: Frequency of Dry Bulb Temperature to Occupied Hours

HARVESTING FROM SQUANDER

In the CH_2 project, the design team took an unconventional approach in setting up the service standards. It breaks away from the industrial norm to allow alternative approaches for the provision of services. This is evidenced in two key areas, the lighting provision for the office spaces, and thermal environment conditions.

Lighting Requirements

In a conventional open plan office, the lighting system is designed to provide a uniform task lighting level on a work plane height over the whole office space. This practice is focused on the flexibility or easy rearrangement and subdivision of the space. According to the Australia Building Greenhouse Rating Scheme (ABGRS) (SEDA, 2004), the occupant density is 18m² of office space per occupant. On average, each workstation has 2m² of desk surface plus 1m² of table surface of meeting room and discussion areas per occupant considered as the work plane. Therefore conventional practice will result in over illuminating more than 85% of the office area which should only be provided with ambient light.

The separation of task light and ambient light is the basis of the energy efficient lighting scheme in CH_2. The lighting system in CH_2 comprises general lighting with an ambient level of 150 lux and local task lighting above individual workstations, providing light level of 320 lux which can be adjusted up to 400 lux by occupants (LSA, 2003). The adjustability of individual task lights for each workstation is enabled by an overall addressable lighting control system which controls lighting to suit the occupancy trend and time of use. A local dimmer control is integrated into the computer screen as an icon. It provides three lighting control options of HIGH, MEDIUM, and LIGHT. The 'Light Level' option will cause a slider to appear with a save button to enable the user to set the light level in close proximity to their workstation area to their preference. The local light fittings will automatically return to the ambient level of 160 lux upon the computer or monitor being switched off.

This control system is beneficial to office workers as they can adjust their preferable light level when performing on screen work or turn up the light when doing paper work. The lighting control concept in CH_2 can deliver considerable energy savings. There is no figure provided by the consultant, however, a recent article from the Property Council of Australia indicates that by adjusting the lighting for people going out for lunch and leaving early alone can achieve a 25% lighting energy cost reduction for general office areas (Hennessy, 2004).

Energy Efficient Lighting

Apart from the sophisticated lighting control systems, CH_2 installed energy efficient fluorescent T5 luminaires in the office levels. The power density of the lighting system is limited to 8W/m². T5 fluorescent lamps are more efficient and last longer than conventional T8 lamps. The standard luminaires provide both downlight and uplight in order to even out the indoor light level which inturn reduces contrast in the space. Electronic dimmable ballasts enable a better light quality and control resulting in less energy use.

Indoor Thermal Requirement

The dominance of deep open plan offices in air conditioned 'glass boxes' in the last few decades has convinced people that they cannot work without air conditioning. Air conditioning has become a necessity in the mindset of contemporary office developers regardless of the climatic potential of the building location. They simply overlook the fact that occupants require a thermally comfortable environment. The term 'thermal comfort' can be defined as a sense of well-being with respect to thermal conditions (ASHRAE, 1992; ISO, 1994). In such a state, a balance between the heat generation from the body (metabolism) and the heat loss through respiration and the skin is achieved (Architect's Council of Europe, 1999; Szokolay, 1995; Givoni, 1974; Fanger, 1970). Thermal comfort is influenced by six objective factors: dry bulb temperature, humidity, air speed, mean radiant temperature , clothing level and metabolic rate.

Considerable energy is wasted in the common practice of the universal set-point temperature control of 22.5°C in a building as prescribed by ASHRAE (1992) and ISO (1994), because it does not allow for the practice of occupants dressing according to the seasons. In the cooler months of the year the temperature can be set at the lower end of the comfort range because occupants tend to be dressed for milder weather. In summer, however, when people 'dress down' for the warmer weather, the temperature setting can be set in the upper end of the comfort range (Hennessy, 2004).

2000 (Facão & Oliveira, 2000).

In the CH_2 project, the space thermal condition is specified by three parameters, namely air temperature, humidity and resultant temperature. A more relaxed air temperature set point of 21 – 25°C can reduce the need for space conditioning. The inclusion on resultant temperature as a parameter allows the design team to incorporate more energy efficient methods of space conditioning. The conventional air conditioning design only specifies dry bulb air temperature set points and relative humidity limits may overlook the importance of the radiant component in space conditioning.

Chilled Ceilings

Chilled ceiling systems provide cooling to the occupants by changing the temperature of the ceiling panel surface instead of cooling the supplied air only. Cooled water running through chilled ceiling panels fixed onto the ceiling can cool the space via natural convection and radiative heat transfer. Radiative heat exchange is more effective to modify the thermal sensation of the human body (Givoni, 1974; Fanger, 1970). Therefore, the system can operate at a higher chilled water temperature compare to ordinary air cooling systems.

Chilled ceilings are not entirely new technology for space cooling, the technology has existed for more than 50 years (TIAX, 2002). This system is more popular in Europe, where about 100,000m² have been installed in central European countries from 1995 to 2000 (Facão & Oliveira, 2000).

In general, radiant ceiling cooling reduces space conditioning energy consumption in several ways.

- In space cooling mode, energy savings accrue from delivering higher chilled water temperatures, 16°C as in the CH_2 project, to the radiant ceiling panels to meet more sensible loads than conventional air conditioning systems. This allows the chiller evaporator temperature to rise and improves chiller efficiency as the temperature difference across the system is lowered. Due to the higher chilled water temperatures used in chilled ceilings, water cooled by evaporative cooling towers can be utilized directly without running the chiller.
- Figure 4 shows the frequency distribution of ambient wet bulb temperature during occupied hours, and indicates that 83% of occupied hours has a corresponding wet bulb temperature lower than 15°C. During the other 17% of the time, the cooling tower can be combined with a chiller to handle the heat load or the energy storage capacity of phase change material freed up by night-cooling (Facão & Oliveira, 2000), as proposed in the CH_2 project.
- The combination of radiant ceiling with displacement ventilation also reduces power by moving only the air required for fresh air supply. The use of water instead of air reduces energy required for cooling delivery as water has a higher heat capacity than air. As a result, radiant ceilings also reduce the heat dissipated by

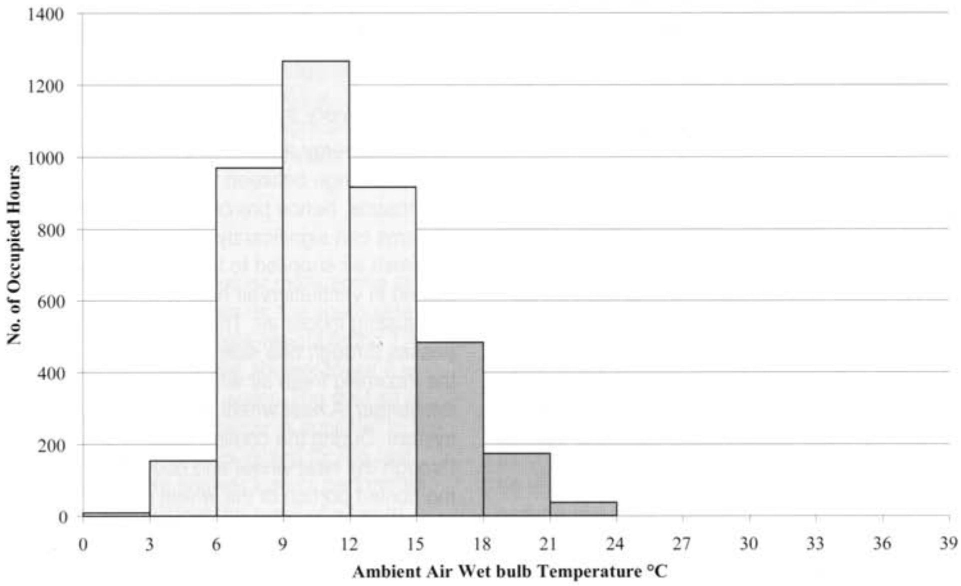

Figure 4: Ambient Wet Bulb Temperature during Occupied Hours

Radiation heat transfer directly cools the occupants, which may allow slightly higher building air temperatures, decreasing building cooling loads. Overall, radiant ceilings reduce cooling energy by 25% to 30% relative to a variable air volume (VAV) system (TIAX, 2002).

Displacement ventilation system

Displacement ventilation systems supply fresh air at floor level at low velocity which pushes the stale polluted warm air up towards the ceiling where it is then exhausted. Displacement ventilation systems harvest the natural buoyancy of air heated up by the internal loads of the building. Displacement ventilation reduces air-conditioning energy consumption relative to conventional mixing ventilation in three ways.

- Displacement ventilation systems can lead to an improved co-efficient of performance (COP) of the chiller due to higher supply air temperature when compared to conventional VAV systems. However, the ability to control humidity is significantly sacrificed. This is particularly important in the CH_2 project as the chilled ceiling system has no ability to remove latent heat and there is a risk of condensation on the panel surface. The higher the standard volume of fresh air supply the more this condition is eased (IEA annex 28, 1995).
- The stratification of room air results in a higher average air temperature than mixing ventilation, reducing building thermal loads by as much as 15% from heat transfer through the building envelope (Hamilton et al., 2004).
- The higher supply air temperature increases potential for utilising cooling towers or outdoor air to meet the cooling need.

In general, displacement ventilation systems have higher fan energy consumption because the system must provide a larger volume of air to each space to meet the cooling loads (Hamilton et al., 2004). In the CH_2 project the displacement ventilation system only has to handle the fresh air supply, as the majority of cooling load is supplied by the chilled ceiling panels. The displacement ventilation system is designed to supply 1.5 l/s/m² of outside air to the building at 19°C and relative humidity < 65%. This combination assists both chilled ceilings and displacement ventilation systems to overcome their traditional weaknesses. The selection of an energy efficient variable speed motor further improves the energy saving of the system.

Energy Efficient Office Equipment

In mainstream offices, computers on each workstation contribute to a significant portion of energy consumption, both in direct electricity consumed by the computer and the heat load to the space conditioning system. As network technology advances, personal computers in all workstations are being replaced by client desktop devices which share the computing power of a centralised server computer. This arrangement reduces the energy consumption of each workstation in CH_2 from 85W for a typical central processing unit down to 8W for a thin client desktop device. The energy saving is further enhanced by adopting liquid crystal display monitors which consume 30W of electricity instead of 80W consume by a cathode ray tube screen. On direct electricity alone, it represents a 77% saving. Savings are also achieved from the 60% reduction in heat released to the space (AEC, 2003b). This reduction in heat load contributes to 11% drop in peak cooling load of the space conditioning system (AEC, 2003c). The isolation of the server enables a dedicated system to remove the unwanted heat which can have significantly higher efficiency as such systems do not need to handle fresh air requirement and latent load since the server room is normally not occupied by people.

HARVESTING FROM WASTE

Useful energy can be recovered from waste produced by various processes that take place in office buildings. In the CH_2 project, two systems are harvesting energy from waste heat. One is the combined cooling, heating and power (CCHP) tri-generation system which recovers heat from on site power generation. The other is the air to air heat recovery system which salvages thermal energy, both warmth and coolth, from exhausting the indoor air stream.

Combined cooling, heating, power tri-generation system

Combined heating and power (CHP) or cogeneration is the simultaneous production of usable heat and electricity in the same power plant. This is not a new technology. In Australia CHP is widely used in hospitals and industrial buildings where needs for large amounts of heat is present. In office building applications, however, it is not as popular because typical office buildings usually cannot utilize all the heat produced by the power plant. In the CH_2 project, the design team integrated the absorption chiller technology into the CHP system to effectively create a CCHP tri-generation system.

The absorption chiller used in CH_2 requires no pumps or other moving parts, but does require a heat source to regenerate liquid absorbent, which replaces the compressor in conventional compressive chillers, to create the pressure difference required for running the refrigeration cycle. Absorption chilling is a key technology in the application of a CCHP system in office buildings because it offers the means to transform heat produced in the power generation process which would otherwise be wasted into cooling. The cooling then can be delivered into the office space for space conditioning. In times of lower cooling needs, the coolth can be used to cool the supply air to the gas turbine which improves the efficiency of gas turbine power generators.

This system significantly improves the primary energy efficiency of the absorption chiller/heat pump. In a traditional sense, an absorption chiller has a coefficient of performance of 0.68 (single stage) to 1.3 (double effect) which is comparatively low to the figure of 4.0 of a conventional chiller system. It does, however, ignore the fact that the energy supplied to the chiller also has an efficiency. Typically in Victoria, the efficiency for a coal power plant is 30 to 33%, and with this consideration, the efficiency of absorption heat pumps can be very competitive.

In the CH_2 project a 60kW capstone dual mode gas microturbine was used. The system generates 60kW of electricity power and 105kW of heat to be utilized by cogeneration plant for heating and cooling. This system will meet 10% of the average building daily electricity demand and meets the required office heating and cooling load for 80% of the operating hours (AEC, 2003c).

There is no specification on the absorption chiller available and critical analysis of the system is not practical. The gas microturbine power generator produces high grade waste heat at 350°C that is capable of triple, double and single effect absorption chiller performance (Sweetser, 2000).

Heat recovery system

Air to air energy recovery heat exchangers are devices which allow heat exchange between the fresh outside air and exhaust indoor air streams, hence pre-conditioning the incoming air. Heat recovery systems can significantly reduce the energy needed to cool or heat the fresh air supplied to the office space. This system is normally placed in ventilation/air handling units that take in fresh air while exhausting indoor air. The exhaust air from the building interior passes through one side of the heat exchanger, counter flow to the incoming fresh air which passes through the other side of the exchanger. A heat wheel is the most common type of heat recovery system. During the cooling season, the cooler indoor air passes through the heat wheel and cools that portion of the wheel. When the cooled portion of the wheel rotates into the hotter outdoor air stream, it pre-cools the incoming outdoor air. The heat exchanger may transfer sensible heat only or it may transfer both sensible and latent heat.

Studies in the US show that heat recovery systems can reduce the annual heating and cooling energy consumption by 35% on VAV air conditioning systems equipped with an economizer cycle in New York (TIAX, 2002). The anticipated energy saving in CH_2 should be significantly lower than the above figure, as the Melbourne climate is considerably milder than New York (AEC, 2003d).

HARVESTING FROM NATURE

Nature is the source of all forms of energy. Harvesting renewable energy that is available onsite can offset the greenhouse gas emissions from consuming fossil fuel.

Daylighting

Artificial lighting systems contribute to 21% of greenhouse gas emission in commercial buildings in Australia (EMET, 1999). Harvesting daylight can significantly reduce the reliance on electric lighting in CH_2. Substituting daylight for artificial light in office space is also an important strategy in reducing the cooling requirement for indoor comfort, as electric lighting contributes to a significant portion of internal heat gain. Daylight in spaces has been shown to increase occupant satisfaction, well-being and improve worker productivity (Leslie, 2003; Capeluto, 2003). In recent years, use of daylighting combined with high performance lighting means that between 30-50% saving can be easily achieved while 60-70% savings are possible in some cases (Architect's Council of Europe, 1999).

Introducing daylight into the office is a challenge for the CH_2 project as the overshadowing effects from surrounding buildings seriously limits the daylight availability for the lower floors. The design addresses this issue by progressively widening the windows on the northern and southern façade from top to bottom. This approach allows more diffused daylight to enter the office at lower levels while restricting excessive solar radiation from striking the top levels. The glazing is specified to have a visible light transmittance above 50% with a solar transmittance below 35%.

Daylight sensors are provided to the office north and south perimeter rows of lighting. Two perimeter rows of fittings are located along the north and south boundaries of the office level. Daylight sensors (five along each side of the office) are provided to compliment natural daylight, and achieve an average illumination of 160 lux. When daylight provides more than 160 lux, these fittings should be switched off. On a cloudy day the daylight sensors will adjust the lighting levels accordingly. After office hours, the daylight sensors would be inactive.

Shower towers

Outside air is drawn in from fourteen metres or more above street level and channelled into the shower towers on the south side of CH_2. The towers are made from tubes of light-weight fabric 1.4 metres in diameter. As the air falls within the shower tower it is cooled by evaporation from the shower of water. The cool air is supplied to the retail spaces and the cool water is supplied to the phase change material where the 'coolth' is stored for the rest of the building when required. These shower towers perform as conventional evaporative coolers without the need of a fan to drive the supply air. The air is driven by the gravitational force on the water droplets and also on the cooler and denser air after the droplets are evaporated (AEC, 2003b).

Solar stack

Ventilation stacks operate when a temperature difference exists between the ambient air and indoor space. Solar stacks are improved ventilation stacks - the solar stacks are painted with a dark colour in order to absorb solar radiation which then heat up the air inside and create an upward force through the buoyancy effect. Six solar stacks are designed to be installed on the north façade of the CH_2 building (AEC, 2003c). These solar stacks are designed as the exhaust path of the office ventilation system. The air flow rate in the stacks is governed by the vertical distance between the inlet and outlet, cross sectional area of the stack and the temperature difference at the inlet and outlet (Chen and Bandopadhayay, 2001). As a result, the cross sectional area of the solar stacks is gradually increased with height so as to maintain a more consistent extraction flow rate amongst all floors. The ventilation effectiveness of the solar stacks is further enhanced by the inclusion of wind turbine ventilators at the top of the solar stacks. The salt bath experiment shows that the solar stack also contributes to the night purge due to their considerable height (CoM, 2004). There is a risk of back flow of exhaust air into the office in cloudy winter days when air inside the stack is colder than the indoor air due to contact with the cold stack envelope (Bansal, 1993). This will induce high pressure to the supply air fans and waste energy. In extreme conditions, this can result in poor indoor air quality.

Wind turbine

Wind energy is one of the most readily available renewable energy sources. The wind turbines proposed for CH_2 are ventilators utilising wind energy to assist air extraction from office spaces. The common wind turbine enhances ventilation about 30% over an open stack (Lechner, 2001). Six wind turbines are to be installed on top of the north solar stacks. The wind turbines improve the night purge ventilation of the building by about 6% on windy nights and do not contribute to ventilation on still nights or during the day (AEC, 2004a). The wind turbines are being developed to generate power during the day.

Phase change material

Phase change material (PCM) is a material that will change its state at a designated temperature in order to absorb or release large amounts of energy. It is the latest member of the thermal energy storage family. It has a higher capacity than water-based thermal storage systems and is more efficient than ice-based storage systems (TIAX, 2002). To the author's knowledge, apart from ice thermal storage systems, there is no PCM application in office cooling on a commercial scale. Other thermal storage systems have also been examined for application in CH_2. These systems included ground coupled thermal storage, and rock bed storage. Based on the micro climate analysis, the design team selected PCM as the thermal storage system for CH_2.

The PCM tank in CH_2 operates like a sponge that release the stored heat at night and acts as a heat sink to soak up heat during the day time. While PCM does not directly harvest coolness, however, it provides the crucial storage for 'coolth' harvested by other components in the complete system which inturn can be utilising when needed. With the PCM in place, the cooling system can take advantage of the cooler night time condition to harvest coolth passively with the cooling towers. Figure 5 shows that in 60% of the reference weather year, the ambient wet bulb temperature is below 12°C and the specified wet bulb temperature to produce cooled water is below 15°C, which is required to freeze the PCM (AEC, 2003f). A study in Switzerland (Facão & Oliveira, 2000) showed that conventional wet cooling towers are greatly overpowered in airflow and spray water rate in the low hot water temperature range as needed for PCM recharging. It leads to energy wasted in fan and pump operation.

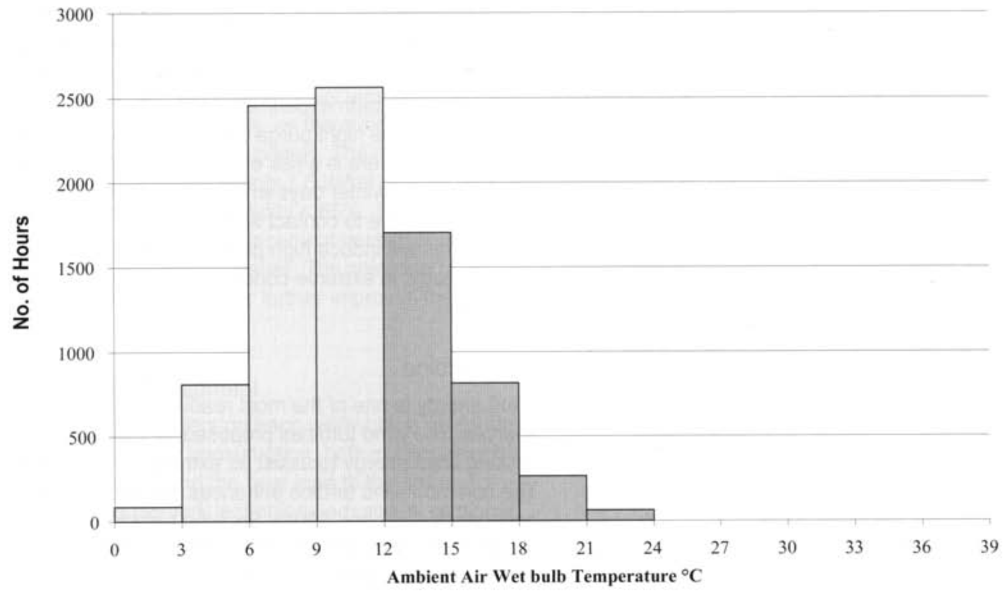

Figure 5: Annual Frequency of Ambient Wet Bulb Temperature

Even in summer time, PCM allows the active cooling system to work more efficiently in two ways. First, it allows the system to operate to its full capacity, since the PCM can satisfy the part load condition. It also reduces the hours of cooling system operation. Secondly, the PCM can shift the peak system load away from the highest outdoor temperature which can improve the ability of the system to efficiently dissipate the rejected heat.

Night purging and thermal mass

In Melbourne, night air is significantly cooler than the daytime air as shown in Figure 6. This cool night air can be used to flush out the heat from a building's thermal mass. The pre-cooled mass can then act as a heat sink during the following day by absorbing heat thus keeping the indoor air temperature from rising as fast as it would otherwise. The CH_2 building relies heavily on the thermal mass effects of its concrete ceiling to cool the building via a night purge ventilation system. In the CH_2 project, natural ventilation cools the building late at night. Automatic operable windows on the north and south façades open to allow fresh cool air to enter the offices, flush out warm air and cool the building. Sensors will close the windows when they detect high winds and rain or ambient temperature higher than indoor temperature. The wind turbines installed at the top of the solar stacks will further enhance the effectiveness of the night-time purging by inducing extra volume of cool night time air in contract with the thermal mass. On still nights, the mechanical ventilation system operates to supplement natural ventilation. Mechanical cooling may be used as required to provide the equivalent night purge benefits when passive night purge is not available. This system should reduce cooling loads by around 14% on a typical summer day (AEC, 2004a).

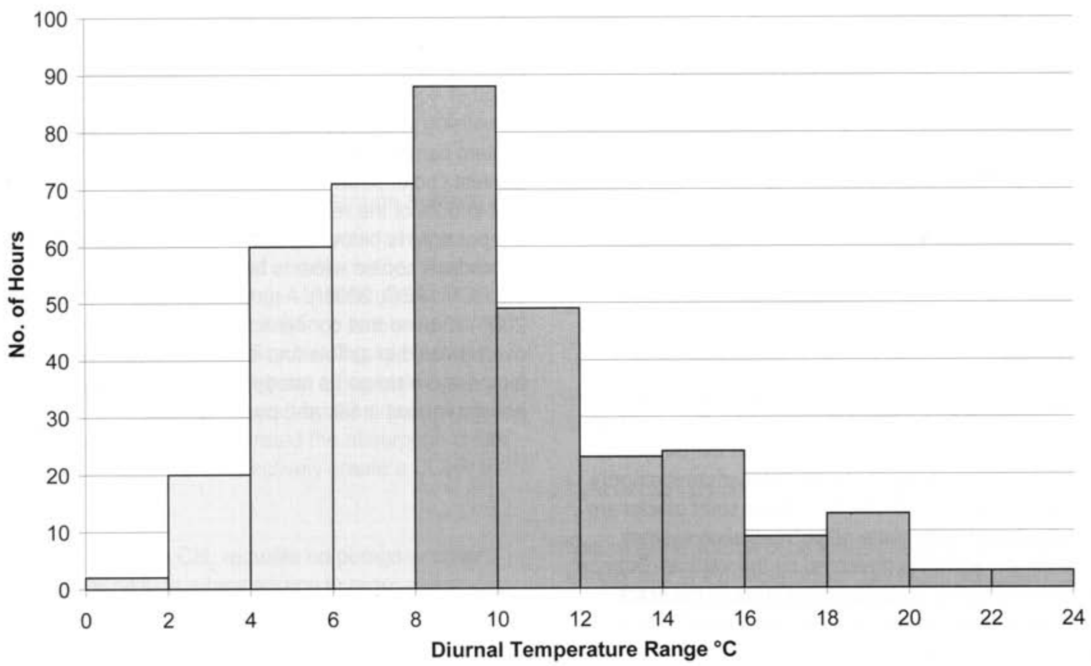

Figure 6: Frequency of Diurnal Temperature Range

Solar hot water system

The solar hot water system captures and uses solar energy in heating the domestic hot water supply. This system has a long history and is widely used in Australia on a residential scale. The solar hot water system proposed for the CH_2 project has a design hot water requirement of 2000 litres per day. The sizing process of the solar hot water system takes into account not only daily demand, but also the optimum amount of panels according to requirements, weather variations and cost implications. A solar hot water system with a panel area of 26m² is proposed to handle about 75% of the hot water requirement, which translates to 20,000kWh per year (AEC, 2003g).

POTENTIAL IMPLEMENTATION

The CH_2 project has taken many steps in developing an energy efficient building. Yet, there are a number of opportunities to further reduce energy consumption.

Daylight redirecting devices such as louvres, highly reflective movable blinds, prismatic panels, and laser-cut panels, to name a few, have the potential to improve the daylight availability to the lower floors (Beltran et al., 1996). These daylight systems could improve the daylight penetration and distribution under overcast and clear sky conditions. Other than installing the daylight redirecting devices in the clerestorey section of windows, a more dramatic design which redirects the winter sun down through light pipes could also be considered.

Desiccant dehumidifiers can be incorporated into the supply air conditioning system for moisture removal. The benefit from desiccant dehumidifying is the superior control over moisture content by separating the sensible and latent conditioning. This can eliminate the over-cooling of the supplied air stream for moisture control, hence reduce the need for chiller power. The typical regeneration temperature of a solid desiccant wheel system is 130°C (Jain et al., 1995) - the exhaust from the tri-generation plant, after powering the absorption chiller, should still be capable to operate such a system. As a result, the efficiency of the integrated system can be further improved by extracting usable lower grade heat from the exhaust of the absorption chiller.

The adaptive comfort model has the potential to further relax the requirements on space thermal conditions (de Dear and Brager, 2002). In the CH_2 project, the temperature set point is considered to be conservative (i.e. 25°C air temperature and 65% relative humidity will result in a predicted mean vote (PMV) of -0.27 if ASHRAE summer clothing level is used). Although a PMV of -0.27 is within the 90% comfort range, it is on the cold side of the PMV scale. A further extension of the temperature limit to 26°C will result in a PMV of 0.1 which is still within the 90% comfort range. The above PMV value is based on minimal air movement and the mean radiant temperature is identical to the air temperature. The chilled ceiling system and the night purged thermal mass will reduce the radiant temperature.

A roof top solar photovoltaic PV array was removed from the final CH_2 design because of the long payback of the system (AEC, 2003g). The estimation is based on a conventional PV array with conversion efficiency of 13.5%. There are alternative technologies that can improve the efficiency and shorten the payback period. Two examples of such systems are solar concentrator systems and improved multi-crystalline solar cells (AGO, 2003). The solar concentrator system uses sun-tracking mirrors to concentrate the direct sun light onto a receiver on the solar cell. This system has a further 15% efficiency in converting sunlight into electricity. This system also generates hot water from pipes running behind the receiver which significantly improve overall efficiency. The multi-crystalline solar cells work under the same principle as conventional PV cells with a conversion efficiency of 17%. It should be noted that the efficiency of PV cells decreases as the panel temperature rises. The utilization of exhausted air from the solar stack to ventilate the PV cells has the potential to improve the conversion efficiency again (Mei et al., 2003).

DISCUSSION

The most important lesson learned from the CH_2 project is the importance of an integrated approach in energy efficient building design. In conventional building design processes, each service is considered as an individual system and the members of the design team tends to work in isolation. The improvement in energy efficiency is limited as all systems are still bonded by conventional practices. In contrast, the CH_2 project treats the building as one system, so each service has become a component only. This approach enables the design team to explore the inter-dependency of various components and the possibility to drastically reduce energy consumption by chain reaction.

From the author's observation, one of these chains reactions in CH_2 is that the building load is first reduced by utilizing low energy equipment and lighting systems and relaxing the space conditioning in both thermal and lighting requirements. This reduced cooling load leads to alternative cooling systems which may not be capable or efficient to condition spaces with ordinary cooling load. This results in the selection of chilled ceiling and displacement ventilation systems as the cooling delivery method. The common characteristic of these two systems is a higher than conventional chilled water temperature. This characteristic enables the use of cooled water directly from cooling towers without the need to operate energy-intensive chillers. It also makes the inclusion of PCM more economically viable as 'coolth' can be produced at night with minimal energy input. The remained cooling is then handled by energy efficient tri-generation plant.

This chain reaction is multiplying the smaller improvement in energy efficiency of individual components which results in significant reduction in energy consumption (Pears, 2004).

Another lesson is that the building energy benchmarks should only be considered as the starting point of an energy efficient building target. Even though the Victorian office benchmarks are the toughest amongst the four benchmarks included in this paper, ESD offices in Victoria show substantial savings over the benchmarks. The limited availability of energy consumption and building performance data has hindered mainstream office buildings from including ESD design features. The available energy consumption figures are only predictions generated by computer simulations. The experiences in the UK show that the actual energy consumption of buildings can be more than three times the predicted consumption (Bordass et al., 2004). This results in damage on the credibility of energy efficiency design principles.

Even the best building energy harvesting systems cannot be successful if the operation control has error. Testing and commissioning is the key to closing the gap between the predicted design performance and the actual building. This should be particularly essential to CH_2 because of the highly integrated and interdependent nature of the services system. The controlling mechanism for each component has to be coordinated to a level which is far more sophisticated than conventional independent systems. The inclusion of post occupancy performance tests in the commissioning plan is a good starting point in ensuring the designed performance is met (AEC, 2004b).

CONCLUSIONS

A new era of environmental and hybrid controlled buildings is at its dawn. The heart and soul of this breed of buildings is a complete departure from the ad-hoc 'environmental buildings' with environmental add-on features applied. Evidence-based knowledge on actual system performance is required for this building type to flourish. The energy performance of the CH_2 project surpasses the design targets of all the energy benchmarks examined in this paper by at least 50%. This high energy performance is achieved by integrating various energy harvesting technologies into the building as a complete system and taking benefits from working with the local climate. The CH_2 project highlights the value of the commitment to the integrated design process and the willingness of all design consultants to invest time and resources to explore alternatives to conventional systems (Luther and Cheung, 2003). New technology, such as the PCM thermal batteries, and the innovative use of more conventional systems, creates a whole new dynamic approach in the provision of required services to the building occupants. The outcomes of the CH_2 project is an exemplary energy efficient building which is expected to provide a first class working environment, if not better, with lower operation cost and greenhouse gas emissions. Building occupants, CoM and the environment should all be winners from this project.

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