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Facilities management added value in closing the energy performance gap

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Abstract

Existing non-domestic buildings tend to use more energy than expected. This paper investigates how the operational strategies of facilities management can contribute to reducing building energy use. A longitudinal case study of a higher education (HE) campus which was conceptualised with the objective of being environmentally friendly and energy efficient is presented. The paper reflects on the energy performance of the campus since its operation in 2001, based on 14 years of energy data and a detailed record of all initiatives undertaken by the campus's facilities management (FM) team in order to optimise energy performance. The integrated FM strategy composed of low- and no-cost strategies, continuous improvements, ongoing commissioning and retrofits succeeded in reducing campus energy intensity from 174 to 87 kWh/(m^2*yr), now outperforming most relevant benchmarks. This finding highlights the importance of operations and maintenance in reducing the energy usage of existing buildings. This presented findings draw on a single case only, which excels through a very detailed longitudinal dataset. Going forwards, the analysis of further cases is recommended to corroborate the findings. The presented results suggest that proactive operations and maintenance strategies in existing buildings can contribute towards significantly improving energy performance. The profile and competency level of facilities management personnel should consequently be raised strategically at the organisational and national/industrial policy level, whilst integrated design processes should be further expanded to include FM's operational control and management in a holistically fashion.

Keywords: Facilities management; Building energy performance; Performance gap; Higher education campus; Operation and maintenance

1. Introduction

Reducing greenhouse gas emissions to avoid dangerous climate change has increasingly become the focus of environmental legislation as well as corporate business and social responsibility agendas (Ernst and Young, 2013; United Nations Global Compact, 2013). Buildings and activities they host are responsible for a significant share of greenhouse gas (GHG) emissions: In 2010, buildings accounted for 35% of total global final energy use (OECD/IEA, 2013), 19% of energy-related GHG emissions, approximately one-third of black carbon emissions, and an eighth to a third of F-gases (IPCC, 2014). Globally, building energy use and related emissions may double or

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potentially even triple by mid-century due to several key trends such as population growth, migration to cities, and increasing levels of wealth and lifestyle changes globally (IPCC, 2014).

Addressing GHG emissions from buildings can, however, also be one of the key mitigation mechanisms since their reduction potentials may be large compared to other major emitting sectors (UNEP-SBCI, 2009). As opposed to other sectors, such as transportation where major low carbon innovations are yet to be expected, many technologies to realise the mitigation potential in buildings are already in existence and well documented (IPCC, 2014). If today's cost-effective best practices and technologies were broadly diffused and implemented, significant carbon savings are possible. The IPCC (2014) further argues that mitigation opportunities in the built environment are often associated with significant co-benefits (such as energy security, health and environmental benefits, improved comfort and services, productivity and net employment gains, increased value for building, etc.), that may exceed the direct benefits by orders of magnitude.

Retrofitting the existing building stock is key to carbon mitigation in built environment because buildings are very long-lived and a large proportion of the total building stock today will still exist in 2050 in developed countries (IPCC, 2014). But initiatives which encourage retrofits at sub-optimal level may "lock in" much of the mitigation potential of buildings, thereby failing to achieve the required level of emission reductions (UNEP-SBCI, 2009). GEA (2012), OECD/IEA (2013) and IPCC (2014) extensively highlight and warn of lock-in effects and risks in both new and existing buildings because of the inability to apply urgent and aggressive state-of-the-art standards on efficiency performance.

At the same time there is overwhelming evidence that many green buildings perform poorly and emit much more CO_2 during actual operation than expected. OECD/IEA (2013) report highlights that many buildings have been designed and built with very efficient technologies and systems and have been recognised with distinction awards such as LEED Platinum and showcased as model buildings, however, their energy consumption is often much higher than expected. Studies of the energy performance of LEED buildings show more mixed results but equally some building perform poorly (Turner and Owens, 2008) – and it was suggested that LEED building certification is not moving towards its goal of climate neutrality (Scofield, 2013; Newsham et al., 2009). Innovate UK's 2014 study on BREEAM rated buildings found that overlooking unregulated energy uses and outdated assumptions on operating hours contributed to the performance gap at the design stage, whilst tick boxing to comply or score more in rating systems instead of taking appropriate design decision for proper use and control during operation was widespread. In particular, it is often cautioned against building controls and systems that are overly complex (CIBSE, 2012). Further, poor construction details as well as the failure to deliver the design intent on-site during construction are problematic (Carbon Trust, 2012).

Whilst aggressive building regulations and standards for new buildings and existing building retrofits are important, there is hence a dire need to addresses these substantial energy performance gaps for buildings in use. Integrated Design Processes (IDP) for the delivery of new buildings and retrofits together with Post-Occupancy Evaluation (POE) may offer ways forwards (Preiser and Vischer, 2005; GEA, 2012; WBCSD, 2009; Harvey, 2009; Lewis et al., 2010), whilst challenges have been reported to effectively applying these two approaches in practice (de Wilde, 2014; Riley et al., 2010; NRF, 2014; National Audit Office, 2007; Carbon Trust, 2012; Harvey, 2013).

Facilities management (FM) may offer important contributions in the face of these challenges. Commercial buildings undergo a major renovation on average every 20–30 years – mostly based on the need for HVAC equipment changes (NEEA, 2014). In the meantime, however, further opportunities to reduce energy costs and carbon emissions should not be overlooked. FM can achieve continuous improvements in building performance through low- and/or no-cost maintenance strategies, retrofits and commissioning, together with proactive operational control and maintenance (O&M) (Aune et al., 2009; Hignite, 2009; Lewis et al., 2010; Hodges, 2012; Finch and Zhang, 2013).

Facilities management is, however, disjointed and the potential contributions of operations and maintenance (O&M) to addressing poor building performance are often overlooked or taken for granted. This paper argues that the holistic inclusion of O&M, i.e., is the domain of facility management, into the integrated design process as part of the building life cycle can make major contributions to reducing the energy use of non-domestic buildings. Such integration will at the same time support FM in focusing on the long term sustainability performance rather than mainly respond to short-term issues arising from either occasional emerging opportunities or opportunistic availability of funds.

Two hypotheses are here proposed:

1. Proactive FM practicing a continuous improvement strategy can majorly reduce the energy performance of a higher education campus.
2. A diligent retrofit based on suitable green rating systems requirements and applied to an existing HE building which has been practicing proactive FM's O&M can further improve energy performance.

They are tested against a longitudinal case study of the long-term FM strategy for an aspirational green HE campus in Singapore. O&M measures and their impact on building energy performance over the course of 15 years are documented.

Implications of the findings for facilities management of HE campuses in tropical climates, building design approaches as well as energy policy and built environment research will be discussed.

2. The role of facilities management in building's energy performance

There is mounting evidence that the energy performance of many existing buildings is sub-optimal. The IFMA 'How-to guide' (2011) finds that over 70% of the existing building stock is consuming more energy than necessary. In the UK, there is evidence that measured electricity demands can be 60–70% higher than those predicted at the design stage in both schools and offices, and over 85% higher in university campuses (CarbonBuzz, 2015).

A number of reasons for poor building performance in use have previously identified at all stages of building conception, design, delivery and operation (Bordass and Cohen, 2004; de Wilde, 2014). Inadequate commissioning, insufficient means of measuring and managing the building systems' performances and poor facility management are amongst other issues identified by Carbon Trust (2012). Finally, the non-existence or incompleteness of commissioning procedures as well as poorly calibrated, commissioned or installed building management systems (BMSs) and a lack of metering hinder the energy efficient operation of buildings, (CIBSE, 2012).

Bordass and Leaman (2015) however highlight that the policy emphasis has long been on design and construction, not performance in use. They argue that post occupancy evaluation (POE) takes a construction industry perspective and conceptualises the handover as the end, not the beginning of efficient building performance. Bordass and Leaman consequently argue that holistic building performance evaluations, including a stronger focus on the operation and maintenance phase, seem recommendable. De Wilde (2014) also highlights that efforts are under way to improve the handover process, such as the 'Soft Landings' process in the UK, yet many problems remain at the operational stage that merit further attention.

Finch and Zhang (2013) finally point out that the realisation of intended environmental improvements depends pivotally on the behaviour of building users as well as on the on-going FM throughout the building's life. They argue that much of the focus has been on the accommodation of sustainable principles in building design and the incorporation of retrofit solutions in the subsequent building life cycle. The fundamental role of the FM in ensuring the continued rectification and improvement of a building's performance can be overlooked due to this focus. They consider 'sustainable buildings' as just that—buildings that achieve high levels of performance, not just from day one, but throughout the building's life and to achieve this, FM plays an indispensable part, tackling the complexities of people, process, and place.

Preventive maintenance and its potential role reduce both operational costs and fuel consumption has also received comparatively little policy attention. Lewis et al. (2010) highlighted that the principal objectives of preventive maintenance are durability, reliability, efficiency and safety. They suggest that the successful operation of green buildings requires proactive maintenance management practices which include preventive and predictive maintenance. And yet, in times of organisational crisis, the FM budget tends to be one of the first to be cut because decision makers often do not understand the benefits of maintenance (Lewis, 1991; Lewis et al., 2010).

Lewis et al. (2010) conclude that the design, installation and operation of many green buildings require systems-thinking and integrated approaches, but both are not currently standard industry practice. They, as well as CIBSE's Guide F (CIBSE, 2012), argue that the installation of highly efficient equipment and systems is only the foundation and the processes used to operate and maintain buildings have larger cost and environmental impacts than the design and construction process. Lewis et al. (2010) suggest based on ASHRAE (2009) that a building with good O&M practices that is poorly designed will often out perform a well-designed building with poor O&M practices. The same argument is raised in CIBSE Guide F (2012).

2.1. Commissioning and retro-commissioning

O&M processes of green building should include, but not limit themselves to the use of benchmarking for decision making, retro and/or re-commissioning, the use of proactive maintenance techniques, the use of rating and certification systems, systems thinking and balancing comfort and energy efficiency (Lewis et al., 2010; CIBSE Guide F, 2012). The European Commission funded project 'Re-Co' presents a number of best-practice case studies for the systematic use of retrocommissioning and other techniques to improve the energy performance in complex buildings, including two universities in Germany and Norway (www.re-co.eu). Details on buildings, energy consumption and improvement measures are published on the online platform, suggesting various measures to improve the linkage of various processes at building level such as for example CO_2 level controlled ventilation or heating controlled schedules with the room booking system. For hospitals, average operational savings potentials were identified to be between 10% and 15%. There is no reason why the same or even more can't be achieved in HE campuses, which tend to have shorter operating hours and be less complex.

Commissioning of new buildings and recommissioning of existing buildings are hence two effective strategies to reduce building energy consumption, costs, GHG emission, and help achieving comfort and meeting sustainability goals (IFMA How-to Guide, 2011; Mills, 2011). Even well-constructed buildings experience performance degradation over time and no matter how well equipment is maintained, if it operates inefficiently or unnecessarily, energy waste and reliability problems can occur (California Commissioning Guide, 2006). Most welloperated and well-maintained facilities that have been commissioned degrade in performance by 10–15% within two to three years after the commissioning is performed. This degradation is the result of multiple factors such as heat exchanger fouling, sensor drift, efficiency reduction and component malfunctioning, etc. which typically go unnoticed (IFMA How-to Guide, 2011). Commissioning often identifies problems that, unless corrected, increase energy use by 20% or more, but is despite such obvious advantages often not done (IPCC, 2014).

Natural Resources Canada (2012) and California Commissioning Guide (2006) highlight that changing occupant needs, space reprogramming, building renovations and obsolete systems erode the efficiency of a building's energy-using systems over time. They recommend to view commissioning as a process that is integrated throughout the building's life cycle rather than as a one-time event. They emphasise that optimum building performance can be maintained by commissioning new buildings or recommissioning existing buildings and then using ongoing commissioning to ensure the persistence of benefits – from the initial conception of a building to its occupancy.

Mills (2011) emphasises that commissioning is a risk-management strategy that should be integral to any systematic approach for energy savings or emissions reductions. He contends that it can simply focus on saving energy by improving conventional building systems, irrespective of whether or not the building is equipped to be particularly energy efficient. Mills emphasises that building commissioning brings a holistic perspective to design, construction, and operation that integrates and enhances traditionally separate functions. It does so through a meticulous "forensic" review of a building's disposition to identify suboptimal situations or malfunctions and the associated opportunities for energy savings.

Retrocommissioning is a process to existing buildings that seeks to improve how building equipment and systems function together, instead of focussing on individual components only. Depending on the age of the building, retrocommissioning can often resolve problems that occurred during design or construction, or address problems that have developed throughout the building's life. Because it takes a holistic approach and addresses the root causes of operational problems, retrocommissioning benefits are more likely to have a long lasting effect according to California Commissioning Guide (2006).

It is generally emphasised that without properly trained facility managers, building operators and technicians for O&M, it will be difficult for the energy efficiency or green building goals of any building to be met (Hodges, 2012). Aune et al. (2009) argue that building operators have the possibility of improving energy efficiency with or without extensive user involvement and with or without advanced technological systems. They highlight a new perspective on the link between FM and energy efficiency which calls into question the approaches focusing on either the behavioural or the technical side of a building's energy consumption. They argue that the "invisible" aspects of the FM's daily work are important in the mediation between technology and use with respect to energy consumption. As FM is able to "see" both users and energy, they are in a unique position to improve the interplay between technology and use and to contribute to more energy efficiency. They strongly recommend rethinking the role of careful "hands-on management" of FM.

3. Methodology: the case study

A longitudinal case study of a higher education campus in Singapore is used to test the hypothesis that proactive FM practicing a continuous improvement strategy can majorly reduce the energy performance of a HE campus and that diligent retrofit based around suitable green rating systems and applied to an existing university building which has been practicing proactive FM's O&M can further improve energy performance. The testing was done by analysing the energy performance of the campus since its operation in 2001, based on 15 years of data and insights collected and interpreted in collaboration with the campus's facilities management (FM) team. Following Flyvbjerg (2006), this case-study could be considered a unique case because very few buildings or campuses have similarly complete records of energy consumption data together with documentations on significant changes to buildings and use (such as changes is floor area or use of space) as well as events and initiatives.

The 16 hectare higher education campus was conceptualised with the objective of being environmentally friendly and energy efficient. It has won several green building awards, namely the ASEAN and BCA award for energy efficient buildings in 2005 and has earned the Gold^{Plus} (in 2009) and Platinum (in 2012) levels of Singapore's building certification scheme Green Mark. The campus has six main buildings of mixed use which overview is presented in Table 1. All buildings are low rise and have between two and six storeys. Sporting activities and physical exercise in the tropical Singaporean climate is facilitated by an outdoor sport canopy (2400 m^2) and the campus is equipped with several car parks for staff and students. The spatial layout of the campus was informed by a study of solar radiation levels for a typical Singapore year. Central spaces, which benefit from intra-block shading, have been landscaped and made useable for teaching facilities and staff offices. The hotter areas in contrast are used for the open car parks and sports facilities.

The site plan was designed such that the majority of the facades are in North–South orientation in order to minimise the amount of solar heat absorbed by the buildings mass. This orientation also takes the advantage of the wind direction for natural cross-ventilation which provides comfort to the many covered link-ways connecting the buildings, open lift lobbies and staircases. For facades in East–West orientation, water feature and vegetation were sited to reduce urban heat effect.

Table 1
Main buildings of the higher education campus.

Block	Name	Main types of spaces	GFA [m^2]
1	Administration	Offices, Meeting Rooms, Data Centre	7909
2	Education	Lecture Theatres, Tutorial & Seminar Rooms, Teaching & Learning Labs, Offices, Child Development Centre	13,219
3	Arts	Music Studio, History Learning Room, Environmental Studies Lab, Tutorial Rooms	19,421
4	Library/Canteen	Library, Canteen	11,846
5	Physical Education	Sports Facilities, Biochemistry lab, Lecture Theatre	25,415
6	Science	Tutorial Rooms, Lecture Theatres, Natural Science & Science Education Labs	25,461
7	Others	Main Lecture Theatre, Playhouse, Art Gallery, Student Hub, Machine Workshop, Kiln & Covered Sports Courts	6545

The envelope of the campus buildings were designed with extensive shading from overhangs, sunscreen and fixed louvres on the exterior walls to reduce cooling loads. Cavity walls were further installed at exterior walls with high sun loads. Natural ventilation, daylighting and skylights are extensively used in corridors, link-ways, the canteen and many lobbies. Along the way, the passive design was enhanced by several refurbishments such as water features, a green roof and thermal and acoustic insulation at the ceiling of the naturally ventilated canteen.

The campus was equipped with a chilled water plant and the originally design was for a primary and a secondary loop chilled water system. A total of 125 air handling units (AHU) were installed for cooling. Out of 125 AHUs, only 11 were constant air volume (CAV) systems, whilst all others enabled variable air volumes (VAV) systems which are considered to be vastly more energy efficient. 9 CAV systems were later retrocommissioned to single zone VAV system with variable frequency drives (VFD) as part of the continuous improvement strategy. The overview of AHUs' technical characteristic is presented in Appendix.

3.1. Campus operational management and maintenance strategy

Continuous attention to operation control and proactive maintenance are considered key parts of the campus' green buildings and energy management strategies. Performance monitoring and tracking together with the logging of events and initiatives were an important part of this concept. The FM team started its energy conservation programme with low-cost/no-cost strategies such as raising some set-point temperatures of spaces and of the chiller as soon as the operation of the campus began in 2001. Table 2 provides a detailed overview of initiatives carried out to improve the energy performance of the campus. Whilst the implemented low-cost/no-cost strategies started to deliver results, the FM team retrofitted and re-commissioned the chilled water system to variable primary flow system in 2003 using VFDs. Continuous monitoring with accurate measurement of network power monitoring/sub-metering system and BAS was applied in 2004. Continuous improvements were further applied for all green initiatives to ensure they worked as intended in practice.

In 2011, the management decided to refurbish all teaching rooms to facilitate a new collaborative teaching pedagogy. The FM team used this opportunity to benchmark this refurbishment against Singapore's Green Mark (GM) building assessment tool and aspired not only to achieve the higher certification level but to go the step beyond. The FM team aspired to achieve chiller efficiencies of 0.6 kW/RT (as opposed to 0.65 kW/RT prescribed in GM-NRB version 4.0) which exceeds the current GM requirement in order to be prepared for the future, more stringent, GM requirements. Energy audits were done again to obtain up-to-date performance data as basis for new designs and a permanent performance measurement and verification (M&V) system was installed. Major recommendations from the GM gap analysis included the retrofit of the chiller plant and the lighting system. All the T8 lights in teaching rooms were retrofitted with T5 lights. Based on energy audits and historical energy logs the chiller sizes were reduced to an optimum of 900 RT. The FM team also recognised the value of accurate M&V and made sure the whole process of design, selection, installation (e.g., making sure that sensors are installed correctly on-site such as 3D/5D for flow sensor in pipes, etc.), commissioning and verification were properly done. The schematic of the new chiller plant is presented in Fig. 1 whilst the look of the plant room before and after the retrofit is presented in Fig. 2.

4. Findings

4.1. Campus energy performance trends

The comprehensive longitudinal record of available energy data allowed for the analysis of trends in campus energy performance. Initially, electrical energy consumption was available only from the main electrical energy metre, but after the installation of comprehensive sub-metering in 2004 the intensity of different end-uses could also be analysed. Yearly energy consumption figures are based on the financial year (from Apr to Mar) as first metre records started in April 2001. The comprehensive facilities management strategy implemented at the higher education campus can be shown to have almost halved campus energy consumption despite a 12% increase in building floor area over the documented period of 14 years (Fig. 3).

Table 2
Record of initiatives carried out for energy performance.

Yr	Initiatives for improvement in energy performance	Strategy and aspect
2001	1. Set chiller and space temperatures higher levels (7.7 °C & 24 °C)	1. Low cost/no cost – behavioural aspect
	2. BMS operator training in better understanding how to use hourly BMS data (chilled water supply & return temperatures as well as air-side AHUs off coil, return temperatures and two way valve positions) when making energy management related decisions	2. Training
	3. Manual monitor and control the sequencing of chillers using BMS hourly data	3. Low cost/no cost – operational control
	4. Adjust chilled water flow to design flow rate as chillers were running higher load due to high flows due to oversights in the initial commissioning	4. Low cost/no cost – retrocommissioning
2002	1. Switch off alternate corridor lights to dim down lighting levels at night (after 11 pm)	1. Low cost/ no cost – operational control
	2. Use of card access system to control air-con and usage based on booking	2. Low cost/no cost – operational control & behavioural aspect
	3. Adjustment of the header by-pass flow in the chiller plant's primary loop following on the replacement of the faulty actuator by-pass line valve	3. Low cost/no cost– retrocommissioning
	4. Use of motion sensors for lights for light control	4. Low cost/no cost – operational control
	5. Put up stickers to remind building users to switch off lights	5. Low cost/no cost – behavioural aspect
	6. Installation of additional standalone Fan Coil Units (FCU) servicing rooms with long operation hours so that original bigger VAV AHUs can be switched off	6. Retrofit – continuous improvement
2003	1. Installation of variable speed drives for chiller pumps	1. Retrofit & retrocommissioning – continuous improvement
	2 Initiate multiple input chiller sequencing.	2. Retrocommissioning – continuous improvement
	3. Install timers to switch off open car park lights at late night	3. Retrocommissioning – continuous improvement
	4. Auto on/off of plant room lights by installing door switch	4. Retrocommissioning – continuous improvement
	5. All lighting control integrated into existing BMS which allowed for more efficient use of the timer programming	5. Retrocommissioning – continuous improvement
	6. Installation of (BAS) time control for Dehumidifiers and fine tune the AHUs' set points for RH control	6. Retrocommissioning – continuous improvement
	7. Installation of Variable Speed Drives (VSD) to CAV AHUs addressing original oversizing	7. Retrocommissioning – continuous improvement
2004	1. Installation of Variable Speed Drives (VSD) to condenser pumps	1. Retrofit & retrocommissioning – continuous improvement
	2. Installed Power Monitoring System – 200 plus sub-metres	2. Retrofit – continuous improvement
	3. Increase night set point temperatures for Fan Coil Units from 22 °C to 26 °C (for some labs to 24 °C)	3. Low cost/no cost – behavioural aspect
	4. Adjust operating hours of Air Handling Units to start half hour later and to stop half hour earlier	4 Low cost/no cost – behavioural aspect
	5. Switch off night chiller and keep running chilled water pump only after midnight	5. Monitoring based commissioning
	6. Integrate Facilities Booking System (FBS) and Building Automation System (BAS) to control air-con/lights supply to teaching rooms by booking	6. Retrofit – behavioural aspect
	7. Remove secondary chilled water pumps and install by-pass chilled water supply line in each of the 6 main buildings	7. Retrofit & retrocommissioning – continuous improvement
2005	1. Reduce minimum frequency limit of Variable Speed Drive (VSD) for Chiller pumps for lower flow	1. Low cost/ no cost – monitoring based commissioning
	2. Installation of electronic filters in AHUs for staff rooms	2 Retrofit – continuous improvement
	3. Installation of (VSD) for MV fans (Kitchen, Chiller Plant)	3. Retrocommissioning – continuous improvement
	4. Reduce wattage of lightings at car-parks	4 Low cost/no cost – retrocommissioning
2006	1. Replacing of Induction lights with energy efficient PLC lamps	1. Retrocommissioning – continuous improvement
	2. Installation of motion sensors to operate VRV air-conditioning	2. Low cost/no cost – operational control & behavioural aspect
	3. Installation of timers to water boilers to Off after office hours	3. Low cost/no cost – operational control & behavioural aspect
2007	1. Reduce wattage of lightings at corridors by re-wiring of circuits	1. Retrocommissioning – continuous improvement
	2. Use of push button to control air conditioning and lightings	2 Low cost/no cost – behavioural aspect
2008	1. Switch on and off air conditioning according to Facilities Booking System's bookings – expanding deployment in all other facilities	1. Low cost/ no cost – behavioural aspect
	2. Modify cross flow sensing tubes and calibrate air-flow sensor and recommission the Building Automation System (BAS) Variable Air Volume (VAV) control for accurate temperature control	2. Retrocommissioning – continuous improvement
	3. Overhaul of Cooling towers – Phase 1	3. Maintenance
	4 Control of Fume cupboards by BAS time schedule	4. Low cost/no cost – operational control

Table 2 (*Continued*)

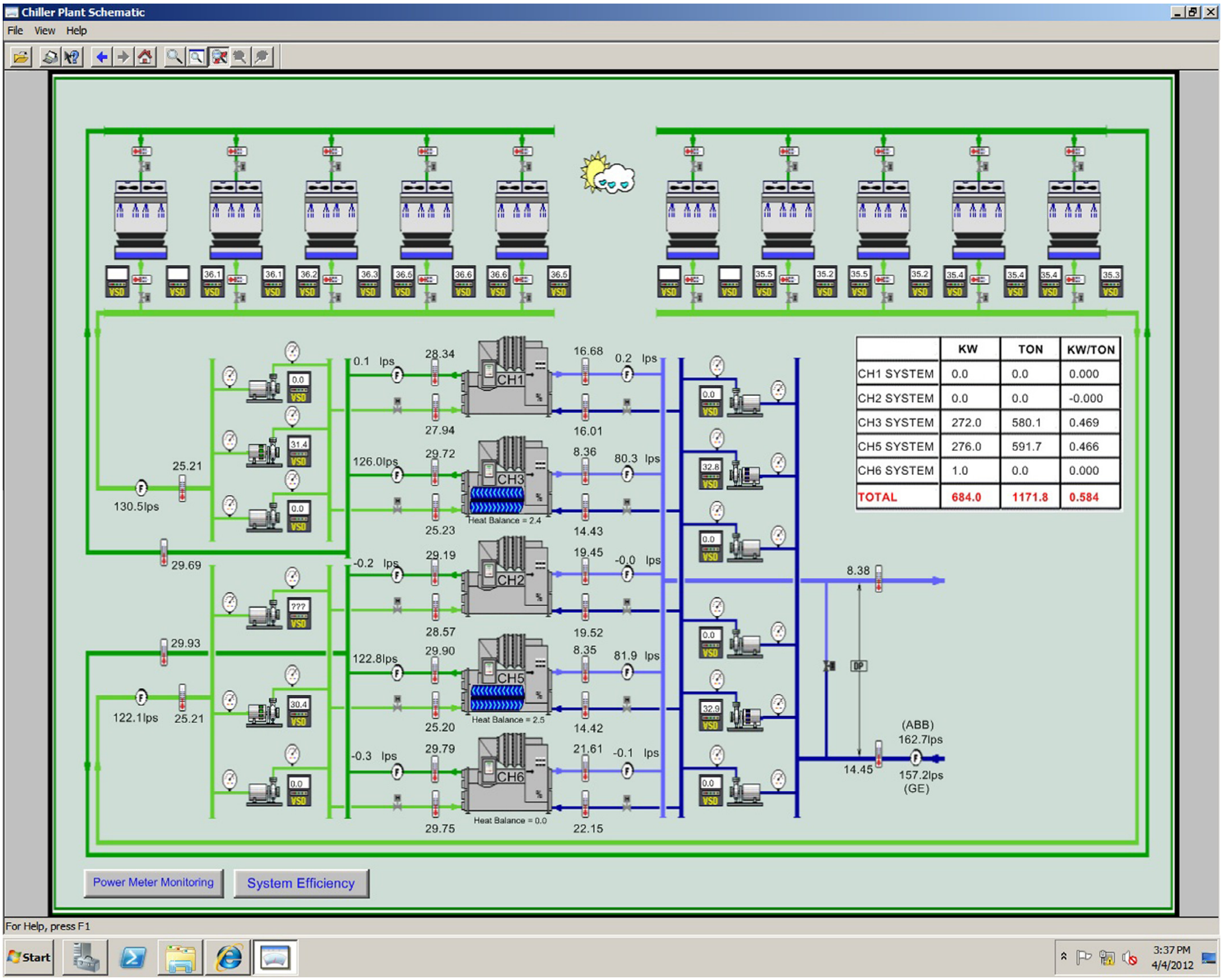
Yr	Initiatives for improvement in energy performance	Strategy and aspect
2009	1. Install Heat Pump to replace electric heaters for shower rooms	1. Retrocommissioning – continuous improvement
	2. DX split type air-cons switched to Chilled water type	2. Retrofit – continuous improvement
	3. Car-parks lights retrofit, further reduced from 110 W to 70 W	3. Retrocommissioning – continuous improvement
	4. Install acoustic and thermal insulation to canteen ceiling	4. Retrofit – passive design improvement
2010	1. Overhaul Cooling Towers – Phase 2	1. Maintenance
	2. Replaced one new efficient VSD chiller for night & weekend load	2. Retrofit & retrocommissioning – continuous improvement
	3. All re-commissioning of VAV thermostat control within ±1 °C	3. Recommisioning
2011	1. Conduct Energy Audit of Chiller plant before major retrofit	1 Energy audit data for feedback to design
	2. Major Chiller Plant Retrofit	2 Retrofit & retrocommissioning – continuous improvement
	3. Green Roof	3. Retrofit – passive design improvement
	4. Lighting Retrofit (T5) for all teaching/tutorial rooms	4 Retrofit – continuous improvement
	5. VRV air-cons replaced to Chilled water type	5. Retrofit & retrocommissioning – continuous improvement
	6. Motion sensors for control of VAV, lights and AHU to close down when no occupancy	6. Retrocommissioning & behavioural aspect
	7. Global Photo Sensors – auto lux level control for corridor & canteen light	7. Retrocommissioning – continuous improvement
2012	1. Retrofit Data Centre – air-con retrofitted from air-cool DX type to chilled water type for primary operation	1. Retrofit & retrocommissioning – continuous improvement
	2. Lighting retrofit phase 2 with T5 and LED for labs and common areas	2. Retrofit – continuous improvement
2013	Lighting retrofit phase 3 with T5 and LED for labs, offices and common areas – approx. 70% total done	Retrofit – continuous improvement
2014	1. Lighting retrofit phase 4 with T5 and LED for balanced areas	1. Retrofit – continuous improvement
	2. Interlock light switch to VAV control in individual staff room – when leaving switching off light will close down VAV damper	2. Retrocommissioning & behavioural aspect

The detailed record of FM initiatives carried out on the campus (see Table 2) further allows a more detailed assessment of how energy savings could be achieved which is presented in Fig. 4. Amongst the FM team's continuous striving for energy performance, four main strategies can be distinguished:

- *Low cost/No-cost strategies:* During the first three years of campus operation, annual energy use intensity (EUI) was reduced by 12% from 174 to 152 kWh/(m^2*yr) through low-cost/no-cost strategies. This result is within the range of 5–20%, which has been stated as potential for such measures (Sullivan et al., 2010).
- *Retrofit and major changes*:
  - o The effect of retrocommissioning is observed as a drastic reduction in energy consumption in both total consumption and chiller plant consumption from 2004 onwards. The main contributor is the retrocommissioning of the chiller pumping system to variable primary flow system. The original primary and secondary chiller pumping system was not functioning and was grossly oversized. The other substantial contributor is the 2004 integration of the Facilities Booking System (FBS) with the building automation system to control air-conditioning /lights to teaching rooms by booking. This initiative is to reduce energy wastage by only providing the services when there is a need (booking) to use the facility.
  - o In 2011/2, a major retrofit to the chiller plant was carried out. The resultant chiller plant performance is 0.58 kW/RT of operating efficiency on average. All the T8 lights in teaching rooms were further replaced with T5 lights based on requirements as specified in Green Mark version 4 (GM-NRB/4.0).
- *Recommissioning:* Two sequences of recommissioning were done in 2008 and 2010 which included some capital investment and mainly encompassed rectification, re-calibration and commissioning of temperature controls.
- *Continuous maintenance and improvement:* Whenever no funds were available for major changes, the proactive FM strategy included a focus on proactive maintenance and continuous improvements with respect to reducing energy consumption. Majorly, this included the re-commissioning of systems and a continuous adaptation of services to the dynamic environment of higher education.

4.2. Campus energy performance compared to peers

Another strategy to evaluate the energy performance of a building is to compare it against is peers, a process commonly known as energy performance benchmarking. In Singapore, the energy use intensities (EUI) of a number



	KW	TON	KW/TON
CH1 SYSTEM	0.0	0.0	0.000
CH2 SYSTEM	0.0	0.0	-0.000
CH3 SYSTEM	272.0	580.1	0.469
CH5 SYSTEM	276.0	591.7	0.466
CH6 SYSTEM	1.0	0.0	0.000
TOTAL	684.0	1171.8	0.584

Figure 1. Screen shot of permanent measurement & verification system showing schematic and operating efficiency of the chiller system.

Figure 2. The HE campus plant room before and after upgrade.

of buildings are available through the mandatory reporting scheme of the Building and Construction Authority (BCA) (BCA, 2014). Performance benchmarks are presented for offices, hotels, retail building and mixed use developments (also including substantial shares of retail). No specific benchmarks are available for higher education campuses in Singapore, likely due to their low numbers. Table 3 hence illustrates a number of other benchmarks which may be useful in framing the performance of the investigated campus despite differences in benchmarked building type or geographical location, i.e., significance of cooling loads.

The energy performance of the investigated higher education campus has improved to 87 kWh/(m^2*yr) as a result

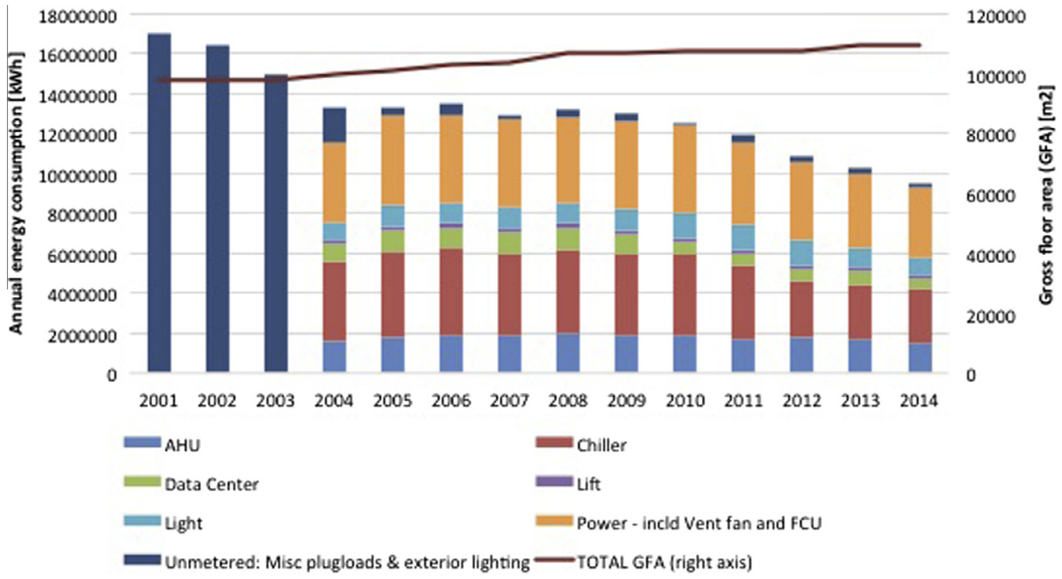


Figure 3. Trend of electrical energy consumptions against the trend of GFA of the campus.

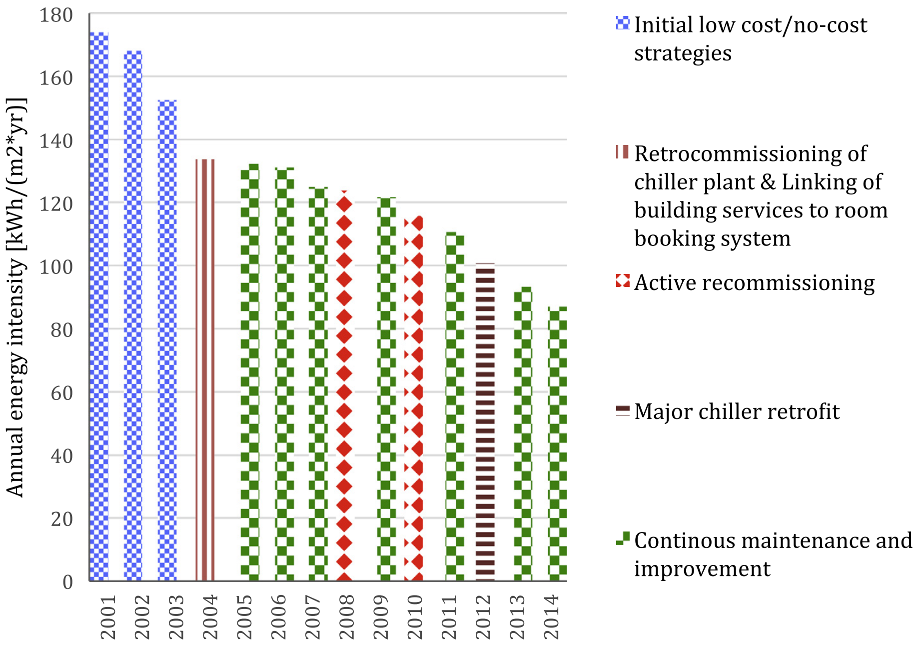


Figure 4. Effect of FM strategies on campus's energy intensity.

Table 3
Campus energy performance against benchmarks.

Source	Building type	Climate	Electricity intensity (median) [kWh/(m^2*yr)]
BCA (2014)	Offices	Singapore	218
	Hotels		292
NRF (2014)	Tertiary Education	Singapore	160
CIBSE TM 46	University Campus	UK	80
This study	University Campus	Singapore	87

of the comprehensive FM strategy including both retrofitting, retrocommissioning and proactive operations and maintenance schemes. Table 3 suggests that this may be regarded as excellent energy performance, especially in the light of the UK campus benchmark of 80 kWh/(m^2*yr) in a climate where cooling loads will be much lower.

5. Discussion

The findings of this study highlight the importance of proactive O&M as key element to reducing the energy demand of buildings. Annual changes in energy consumption were further linked to the main type of initiative undertaken, whilst the FM team instigated a number of different changes every year as illustrated in Table 2. Such

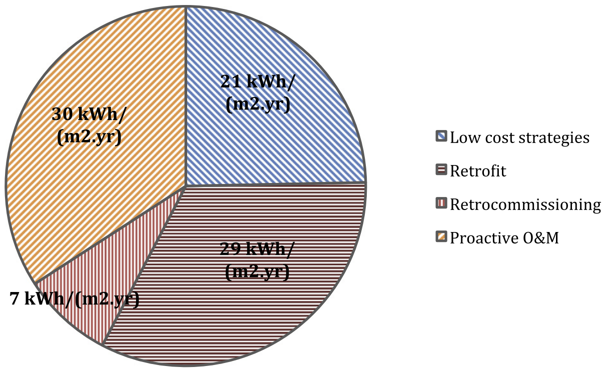


Figure 5. Improvements in energy performance per type of measures.

indicative findings for this campus, however, suggest that proactive O&M strategies may achieve energy savings in a similar order of magnitude as retrofits and low cost or no cost measures (Fig. 5).

5.1. Integrated facilities management with strong O&M focus

Additionally, a number of other observations were made which highlight the importance of O&M in ensuring optimal building energy performance. Firstly, building certification schemes, energy policy and built environment research in tropical climates tend to focus on the efficiencies of chiller plant and ways to improve them. This study, however, has shown that whilst the retrofitting of chiller plants in existing buildings is essential, it may offer only a partial solution to optimising energy performance.

Overcooling (NRF, 2014) as well as a lack of maintenance and proper control on demand side (AHU, FCU, VAV terminals) will still create unnecessary high cooling load if unaddressed. To avoid such situations, it is recommended to give priority to the analysis and accurate definition of service requirements on demand side as recommended by principles of integrated design. Demand-side efficiency and energy performance should be measured, benchmarked and controlled with equal focus and importance as supply side (chiller plant).

In this case study, average cooling loads were reduced by 25% before carrying out the major retrofit of the chiller plant in 2011 as a result of retrocommissioning and continuous improvement efforts of the proactive facilities management team. This not only improved energy performance during that period but also subsequently reduced the capital investment required for the chiller retrofit. This example further highlights the interconnectedness of the different strategy elements as well as of demand and supply side considerations. The presented results demonstrate that in contrast to short-term decision making often done in silo or piecemeal steps, operational management set within the context of continuous improvements and appropriate green building rating system can deliver major benefits.

5.2. The FM and the performance gap in existing buildings

Much has been written over the last years about the ‘performance gap’, the difference between the design and the operational energy use in new buildings (e.g., CIBSE TM 54). It does, however, remain unclear how long a building classifies as a new building and after how many years it becomes an existing building. There is further little certainty how performance gaps are defined in existing buildings, despite evidence that buildings will most certainly improve their performance following retrofits or other initiatives (BCA, 2014).

It will hence seem that the ‘performance gap’ concept has been useful to uncover the mismatch between design and actual performance in ‘new-ish’ buildings. It has, however, focussed strongly on unregulated energy uses and occupant behaviours as main reasons. This study found that the electricity use for small power accounted for 22–24% of total electricity use in the investigated university campus (Small power consumption was estimated by subtracting the consumption of MV and FCU based on installed equipment power and operating hours inclusive of estimated management factors from the measured power consumptions shown in Fig. 3). But despite this significant load share from small power equipment, the overall performance of the campus could be shown to be excellent both against its historical performance and in comparison to its peers.

It may hence be argued that the inability to centrally control the electricity consumption from the use of appliances (such as lab equipment, computers in computer labs, essential IT equipment and other plug-loads) must not necessarily limit a building’s energy performance level as these can be overcome by the holistic O&M of FM. Moving forwards, the research and professional activities aimed at closing the performance gap may consequently want to re-focus its attention to include shortcomings within regulated energy uses and well as paying increased attention to operational control. More specific than a mere ‘performance gap’, there may be a ‘FM gap’ in existing non-domestic buildings. If so, the FM gap can closed through the more wide-spread recognition of the important role of FM in reducing carbon emissions, training for FM staff and adequate policy support.

6. Conclusions and recommendations

This paper aimed to illustrate the important contribution of facilities management in general and in operations and maintenance in particular in reducing the energy use of non-domestic buildings. Much evidence in the literature has highlighted the need to focus on building energy performance in-use as opposed to design or regulated performance because actual performance was often found to significantly exceed predictions. Several reasons have been identified for this ‘performance gap’, including unregulated operational loads and extended operating hours. This study has additionally highlighted the importance of proactive operational control and maintenance to ensure building performance is at its optimum.

A longitudinal case study of a campus was presented containing a complete 15 year record of energy consumption data in combination with the documentation of significant changes, events and initiatives. As a new-built, the campus had an energy performance of 174 kWh/(m^2*yr) in 2001. Due to a number of low or no cost strategies as well as retrocommissioning and proactive maintenance aimed at continuous improvements, over the course of 11 years, the energy performance improved by 36% to 111 kWh/(m^2*yr) in 2012 despite the increase in total treated floor area. Following a major retrofit of the chiller plant as well as the lighting installations in all teaching rooms in combination with on-going operations control and maintenance efforts the campus achieved an energy performance of 87 kWh/(m^2*yr) in 2014. Both in the light of its historic energy performance and in comparison to relevant benchmarks, this performance may be regarded as excellent.

An integrated facilities management strategy with a strong focus on proactive O&M aimed at continuous improvement may be considered the key to this success. The FM strategy further included (but was not limited to) low-cost/no-cost strategies, ongoing commissioning as well as retrofits, the latter of which were found to be both more effective and more cost-efficient due to the optimised baseline energy performance and the rich record of data obtained through the continuous improvement strategy. Based on the limited experience of this one case study, it is suggested that proactive O&M strategies in existing buildings may contribute to energy performance in a similar order of magnitude as retrofits and low cost measures.

Proactive O&M strategies as well as all types of commissioning and retrocommissioning should therefore be given more attention in practice as well as in policy making and research. The competency, skill base and motivation levels of FM teams may be some of the crucial enablers for proactive O&M practices. It is recommended that the profile and competency level of facilities management personnel be raised strategically at national level through relevant initiatives.

Integrated design processes and post occupancy evaluation attempts should be further expanded to include FM's operational control and management in a holistically integrated approach, giving appropriate attention to each element: Passive design features such as an appropriate building orientation contributed significantly to the low energy performance of the campus investigated in this study. The resizing of the chiller plant prior to the 20 years often assumed as plant replacement cycle was also shown to achieve fuel and carbon savings following a continuous reduction in site cooling load. Both examples highlight the interconnectedness of the different strategy elements as well as of demand and supply side considerations. Only the concerted and holistic action during design, construction, commissioning, retrofitting to stringent as well as proactive O&M can hence ensure optimal building performance, with facilities management being a key but so far sometimes overlooked part of any integrated approach.

Appendix A

Technical characteristics of campus AHUs.

S/no.	Brand	Airflow CMH	Motor KW	Remarks
1	York	26,000	11.0	AHU-AD-L1-1
2	York	26,200	11.0	AHU-AD-L2-1
3	York	2400	11.0	AHU-AD-L2-2
4	York	5400	2.2	AHU-AD-L2-3
5	York	11,520	3.0	AHU-AD-L2-4
6	York	28,200	15.0	AHU-AD-L3-1
7	York	30,000	15.0	AHU-AD-L3-2
8	York	20,000	15.0	AHU-AD-L4-1
9	York	11,520	5.5	AHU-AD-L4-2
10	York	5400	3.0	AHU-AD-L4-3
11	York	9700	4.0	AHU-ED-B1-1
12	York	7500	4.0	AHU-ED-B1-2
13	York	6750	3.0	AHU-ED-B1-3
14	York	18,000	11.0	AHU-ED-B1-4
15	York	14,120	7.5	AHU-ED-B1-5
16	York	10,500	5.5	AHU-ED-B1-6
17	York	12,800	7.5	AHU-ED-L1-1
18	York	11,000	5.5	AHU-ED-L1-2
19	York	22,000	11.0	AHU-ED-L1-3
20	York	12,800	7.5	AHU-ED-L1-4
21	York	5025	3.0	AHU-ED-L2-1
22	York	5025	3.0	AHU-ED-L2-2
23	York	19,380	11.0	AHU-ED-L2-3
24	York	19,420	11.0	AHU-ED-L2-4
25	York	27,280	15.0	AHU-ED-L2-5
26	York	16,873	11.0	AHU-ED-L3-1
27	York	18,700	11.0	AHU-ED-L3-2
28	York	3240	1.1	AHU-ED-L3-3
29	York	3240	1.1	AHU-ED-L3-4
30	York	23,530	15.0	AHU-ED-M-1
31	York	24,923	15.0	AHU-ED-M-2
32	York	9400	4.0	AHU-ART-B2-1
33	McQuay	10,044	5.5	AHU-ART-B1A-1
34	York	29,800	11.0	AHU-ART-B1-1
35	York	20,900	11.0	AHU-ART-B1-2
36	York	18,175	7.5	AHU-ART-B1-3
37	York	16,200	11.0	AHU-ART-B1-4
38	York	6000	3.0	AHU-ART-B1-5
39	York	9000	3.0	AHU-ART-B1-6
40	York	15,560	7.5	AHU-ART-B1-7
41	York	16,340	7.5	AHU-ART-B1-8
42	York	9950	4.0	AHU-ART-B1-9

(continued on next page)

Appendix A (*continued*)

S/no.	Brand	Airflow CMH	Motor KW	Remarks
43	York	6000	3.0	AHU-ART-B1-10
44	York	7000	3.0	AHU-ART-B1-11
45	York	7780	4.0	AHU-ART-B1-12
46	York	17,600	7.5	AHU-ART-L1-1
47	York	9600	4.0	AHU-ART-L1-2
48	York	24,000	11.0	AHU-ART-L1-3
49	York	19,200	11.0	AHU-ART-L1-4
50	York	11,000	5.5	AHU-ART-L2-1
51	York	21,750	11.0	AHU-ART-L2-2
52	York	19,200	11.0	AHU-ART-L2-3
53	York	7600	3.0	AHU-ART-L2-4
54	York	15,000	7.5	AHU-ART-L2-5
55	York	23,800	11.0	AHU-ART-L2-6
56	York	14,400	5.5	AHU-ART-L2-7
57	York	11,560	5.5	AHU-ART-L2-8
58	York	22,500	11.0	AHU-ART-L2-9
59	York	24,000	15.0	AHU-ART-L3-1
60	York	25,500	15.0	AHU-ART-L3-2
61	York	3240	1.1	AHU-ART-L3-3
62	York	3240	1.1	AHU-ART-L3-4
63	York	25,450	15.0	AHU-ART-M-1
64	York	38,090	22.0	AHU-ART-M-2
65	York	3450	1.1	AHU-LIB-B2-1
66	York	6500	3.0	AHU-LIB-B1-1
67	York	33,100	18.5	AHU-LIB-L2-1
68	York	32,800	15.0	AHU-LIB-L2-2
69	York	33,100	15.0	AHU-LIB-L3-1
70	York	32,800	15.0	AHU-LIB-L3-2
71	York	58,600	30.0	AHU-LIB-L4-1
72	York	32,800	30.0	AHU-LIB-L4-2
73	York	24,600	11.0	AHU-PE-B3-1
74	York	12,800	5.5	AHU-PE-B3-2
75	York	26,800	22.0	AHU-PE-B3-3
76	York	11,520	7.5	AHU-PE-B2-1
77	York	12,800	11.0	AHU-PE-B2-2
78	York	11,520	7.5	AHU-PE-B2-3
79	York	18,800	7.5	AHU-PE-B1-1
80	York	8200	4.0	AHU-PE-B1-2
81	York	7450	4.0	AHU-PE-L1-1
82	York	12,000	5.5	AHU-PE-L1-2
83	York	26,800	11.0	AHU-PE-L1-3
84	York	6400	3.0	AHU-PE-L1-4
85	York	12,800	5.5	AHU-PE-L1-5
86	York	50,400	30.0	AHU-PE-L2-1
87	York	50,400	22.0	AHU-PE-L2-2
88	York	50,400	22.0	AHU-PE-L2-3
89	York	13,280	5.5	AHU-PE-L2-4
90	York	15,690	7.5	AHU-PE-L2-5
91	York	13,500	5.5	AHU-PE-L2-6
92	York	5670	3.0	AHU-PE-L3-1
93	York	6820	3.0	AHU-PE-L3-2

Appendix A (*continued*)

S/no.	Brand	Airflow CMH	Motor KW	Remarks
94	York	50,400	22.0	AHU-PE-L3-3
95	York	50,400	22.0	AHU-PE-L3-4
96	York	16,500	7.5	AHU-PE-L3-5
97	York	3240	1.1	AHU-PE-L3-6
98	York	21,450	11.0	AHU-PE-M-1
99	York	13,500	7.5	AHU-PE-M-2
100	York	9770	4.0	AHU-SC-B3-1
101	York	35,300	15.0	AHU-SC-B2-1
102	York	13,775	7.5	AHU-SC-B2-2
103	York	11,400	5.5	AHU-SC-B2-3
104	York	36,700	15.0	AHU-SC-B1-1
105	York	17,000	11.0	AHU-SC-B1-2
106	York	18,500	11.0	AHU-SC-B1-3
107	York	23,400	11.0	AHU-SC-B1-4
108	York	17,000	11.0	AHU-SC-B1-5
109	York	30,265	15.0	AHU-SC-B1-6
110	York	9700	4.0	AHU-SC-B1-7
111	York	19,200	11.0	AHU-SC-L1-1
112	York	24,000	15.0	AHU-SC-L1-2
113	York	24,000	15.0	AHU-SC-L1-3
114	York	19,200	11.0	AHU-SC-L1-4
115	Trane	27,612	15.0	AHU-SC-L1-5
116	Trane	11,200	3.0	AHU-SC-L1-6
117	York	25,150	15.0	AHU-SC-L2-1
118	York	22,690	11.0	AHU-SC-L2-2
119	York	22,690	11.0	AHU-SC-L2-3
120	York	19,000	11.0	AHU-SC-L2-4
121	York	11,200	4.0	AHU-SC-L2-5
122	York	23,000	15.0	AHU-SC-L3-1
123	York	31,200	15.0	AHU-SC-L3-2
124	York	8400	4.0	AHU-SC-L3-3
125	York	18,000	11.0	AHU-SC-L3-4
126	York	19,800	11.0	AHU-SC-L3-5
127	York	13,500	7.5	AHU-SC-L3-6
128	York	3240	1.1	AHU-SC-L3-7
129	York	3240	1.1	AHU-SC-L3-8
130	York	3240	1.1	AHU-SC-L3-9
131	York	24,350	15.0	AHU-SC-M-1
132	York	24,240	15.0	AHU-SC-M-2
Total		2,385,577 CMH	1245.1 kW	

References

Aune, M., Berker, T., Bye, R., 2009. The missing link which was already there. Facilities 27 (1/2), 44–55. http://dx.doi.org/10.1108/02632770910923081.

Bordass, Cohen. (2004). Energy performance of non-domestic buildings: closing the credibility gap. In: Proceedings of the 2004 Improving Energy Efficiency of Commercial Buildings Conference. <http://www.usablebuildings.co.uk/Pages/Unprotected/EnPerfNDBuildings.pdf> (accessed 18 June 2015).

Bordass, B., Leaman, A. (2015). Building performance assessment and evaluation. In: Paper presented at PART 1. 2, Building Performance Sessions, 12 May 2015, Centre for Alternative Technology (CAT), Machynlleth. <www.usablebuildings.co.uk> (accessed 18 June 2015).

Building and Construction Authority (BCA), 2014. Building Energy Benchmarking Report 2014. Building and Construction Authority (BCA) of Singapore, Singapore.

California Commissioning Collaborative, 2006. California Commissioning Guide: Existing Buildings. California Commissioning Collaborative, <http://www.cacx.org/resources/documents/CA_Commissioning_Guide_Existing.pdf> (accessed 20 June 2015).

Carbon Trust, 2012. Closing the Gap: Lessons Learned on Realising the Potential of Low Carbon Building Design. The Carbon Trust, London.

CarbonBuzz (website) (London: Chartered Institution of Building Services Engineers/Royal Institute of British Architects). <http://www.carbonbuzz.org> (accessed 15 July 2015).

CIBSE Guide F, 2012. Energy Efficiency in Buildings. CIBSE Guide F, third ed. The Chartered Institution of Building Services Engineers, London.

de Wilde, P., 2014. The gap between predicted and measured energy performance of buildings: a framework for investigation. Autom. Constr. 41, 40–49.

Ernst, Young, 2013. Six growing trends in corporate sustainability <http://www.ey.com/Publication/vwLUAssets/Six_growing_trends_in_corporate_sustainability_2013/$FILE/Six_growing_trends_in_corporate_sustainability_2013.pdf> (last accessed 24 August 2015).

Finch, E., Zhang, X., 2013. Facilities management. In: Design and Management of Sustainable Built Environments. Springer, London, pp. 305–326.

Flyvbjerg, B., 2006. Five misunderstandings about case-study research. Qual. Inq. 12 (2), 219–245.

GEA, 2012. Toward a Sustainable Future. IIASA and Cambridge University Press, Laxenburg, Austria and Cambridge, UK.

Harvey, L., 2009. Reducing energy use in the buildings sector: measures, costs, and examples. Energy Effic. 2 (2), 139–163.

Harvey, L., 2013. Recent advances in sustainable buildings: review of the energy and cost performance of the state-of-the-art best practices from around the world. Annu. Rev. Environ. Resour. 38 (1), 281–309.

Hignite, K., 2009. The Educational Facilities Professional's Practical Guide to Reducing the Campus Carbon Footprint. APPA: Association of Higher Education Facilities Officers (NJ1).

Hodges, C. (2012). High-performance buildings need high-performance FM. In: World Workplace Asia, July 2012.

IFMA How-to Guide, 2011. Sustainability "How-to Guide Series" – Commissioning Existing Buildings. IFMA Foundation.

IPCC, Lucon, O., Ürge-Vorsatz, D., Ahmed, A.Z., Akbari, H., Bertoldi, P., Cabeza, L.F., et al. (2014). Buildings. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. <http://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_chapter9.pdf> (accessed July 2015).

Lewis, D., 1991. Turning rust into gold: planned facility management. Public Administration Rev. 51 (6), 494.

Lewis, A., Riley, D., Elmualim, A., 2010. Defining high performance buildings for operations and maintenance. Int. J. Facility Manage. 1 (2).

Mills, E., 2011. Building commissioning: a golden opportunity for reducing energy costs and greenhouse gas emissions in the United States. Energy Effic. 4 (2), 145–173.

National Audit Office, 2007. Building for the Future. Sustainable Construction and Refurbishment on the Government Estate. TSO, London, <http://www.nao.org.uk/wpcontent/uploads/2007/04/0607324.pdf> (last accessed 24 August 2015).

Natural Resources Canada, 2012. Building Commissioning and Recommissioning Fact Sheet. Natural Resources Canada, <http://www.nrcan.gc.ca/sites/www.nrcan.gc.ca/files/oee/files/pdf/publications/commercial/CxRCx_eng.pdf> (accessed 20 June 2015).

NEEA, 2014. Northwest Commercial Buildings Deep Energy Retrofit Twenty Year Market Base Assessment <https://neea.org/docs/default-source/reports/northwest-commercial-buildings-deep-energy-retrofit-market-characterization-and-twenty-year-market-baseline.pdf?sfvrsn=5> (accessed 26 July 2015).

Newsham, G., Mancini, S., Birt, B., 2009. Do LEED-certified buildings save energy? Yes, but.... Energy Build. 41 (8), 897–905.

NRF, 2014. Building Energy Efficiency R&D Roadmap. National Research Foundation Singapore.

OECD/IEA, 2013. Transition to Sustainable Buildings – Strategies and Opportunities to 2050. OECD/IEA.

Preiser, W., Vischer, J.C. (Eds.), 2005. Assessing Building Performance. Elsevier, Oxford.

Riley, M., Kokkarinen, N., Pitt, M., 2010. Assessing post occupancy evaluation in higher education facilities. J. Facilities Manage. 8 (3), 202–213.

Scofield, J., 2013. Efficacy of LEED-certification in reducing energy consumption and greenhouse gas emission for large New York City office buildings. Energy Build. 67, 517–524.

Sullivan, G.P., Pugh, R., Melendez, A.P., Hunt, W.D. (2010). Operations and Maintenance Best Practices. A Guide to Achieving Operational Efficiency, US Department of Energy, <http://energy.gov/sites/prod/files/2013/10/f3/omguide_complete.pdf> (accessed July 2015).

Turner, C., Council, U.G.B., and Owens, B. (2008). Energy Performance of LEED® for New Construction Buildings. <http://www.usgbc.org/Docs/Archive/General/Docs3930.pdf> (accessed March 2015).

UNEP-SBCI (United Nations Environment Programme Sustainable Buildings Climate Initiative), 2009. Buildings and Climate Change: Summary for Decision Makers. UNEP SBCI, Paris, France.

United Nations Global Compact. (2013). The Global Corporate Sustainability Report 2013. <https://www.unglobalcompact.org/docs/about_the_gc/Global_Corporate_Sustainability_Report2013.pdf> (last accessed 24 August 2015).

WBCSD, 2009. Energy Efficiency in Buildings – Transforming the Market, The Energy Efficiency in Buildings Project. The World Business Council for Sustainable Development.