

9th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC) and the 3rd International Conference on Building Energy and Environment (COBEE)

Performance Analysis of Solar Desiccant-Evaporative Cooling for a Commercial Building under Different Australian Climates

Yunlong Ma*, Lisa Guan

Queensland University of Technology (QUT), 2 George Street, Brisbane, 4000, Australia

Abstract

This paper evaluates and compares the system performance of a solar desiccant-evaporative cooling (SDEC) system with a referenced conventional variable air volume (VAV) system for a typical office building in all 8 Australian capital cities. A simulation model of the building is developed using the whole building simulation software EnergyPlus. The performance indicators for the comparison are system coefficient of performance (COP), annual primary energy consumption, annual energy savings, and annual CO₂ emissions reduction. The simulation results show that Darwin has the most apparent advantages for SDEC system applications with an annual energy savings of 557 GJ and CO₂ emission reduction of 121 tonnes. The maximum system COP is 7. For other climate zones such as Canberra, Hobart and Melbourne, the SDEC system is not as energy efficient as the conventional VAV system.

© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of the organizing committee of ISHVAC-COBEE 2015

Keywords: Solar air conditioning; Desiccant dehumidification; Evaporative cooling; Australian commercial building; HVAC

1. Introduction

Buildings contribute to a large proportion of global energy depletion and greenhouse gas emissions during construction and operation stages. Research shows that in Europe, buildings account for 39% total energy consumption, among which 26% is for residential buildings and 13% for commercial architectures [1]. In China, 25~30% of the total national primary energy is consumed by civil and industrial buildings [2]. While in America, buildings represent 40% total energy consumption, of which two thirds are consumed by commercial buildings [3].

* Yunlong Ma. Tel.: +61 424150330

E-mail address: yunlong.ma@student.qut.edu.au

A similar situation occurs in Australia which is pointed out by [4] that the building industry consumes 40% of the nation's total produced electricity, within which 61% is used by commercial buildings. They also conclude that the largest building energy consumption is from the heating, ventilating, and air conditioning (HVAC) systems.

Australia has a rich solar energy resource with the highest average solar radiation per square meter in the world [5]. The average annual solar radiation gathered in Australia is approximately 58 million petajoules (PJ), which is nearly 10,000 times of the nation's annual energy consumption [6]. Therefore, solar air conditioning technology is considered to be an attractive substitution of conventional vapor compression HVAC system to achieve indoor air quality improvement and energy consumption reduction due to its energy efficient and environmentally friendly characteristics, especially for commercial buildings [7]. Recently solar desiccant air conditioning technology has been widely studied in the world, including Hong Kong [8-14], China [15,16], Malaysia [17], UK [18], Italy [19] and Australia [7,20-22]. For example, Baniyounes et al. [20] conducted a comparison study between solar desiccant cooling system and solar absorption cooling system for an institutional building in central Australian subtropical climate using TRNSYS. They demonstrated that both systems could achieve higher energy savings and system COP by increasing solar collector areas. However, solar desiccant cooling system has higher COP and solar fraction than solar absorption cooling system.

The purpose of this paper is to evaluate the potential of solar desiccant-evaporative cooling technology for a typical commercial building in different Australian climates. Specifically, this paper will compare the performance of the SDEC system with a referenced conventional VAV HVAC system in all Australian capital cities, namely Adelaide, Brisbane, Canberra, Darwin, Hobart, Melbourne, Perth, and Sydney. The investigation aims at finding out whether solar desiccant air conditioning system is technically and environmentally feasible for Australia.

2. Methods

In order to assess the energy performance of the SDEC system and the VAV system, a year round (8760 hours) simulation is conducted for each city using computer simulation software EnergyPlus. EnergyPlus is a whole building energy analysis tool which simulates the actual operations of the building and its HVAC system to predict annual operational cost and energy consumption.

2.1. Building model and SDEC system configuration

The building model and SDEC system diagram is shown in Figure 1 below. The building to be modelled is a 5-zone, rectangular, three-storey office building with a basement car park, which is recommended by the Australian Building Codes Board (ABCB) as Building Type B (long axis East-West), to represent a typical medium sized commercial building in the central business district of the capital cities in Australia [23]. The total conditioned space is 2003.85 m². The U value for roof is 0.277 W/m²K, and 1.32 W/m²K for floor, 0.554 W/m²K for wall, and 5.89 W/m²K for window with the window-to-wall ratio of 0.4. The internal loads are: 10 m²/person for occupancy, 15 W/m² for both lighting and equipment, and 10 L/s/person for outside air rate. The indoor design conditions are: 24 °C, 50% relative humidity for cooling, and 20 °C for heating. To reduce energy consumption, the SDEC system is operated only when the outdoor air dry bulb temperature is above 18 °C and humidity ratio is higher than 0.008 kg/kg. It is controlled by a sensor that provides an on/off signal to pumps.

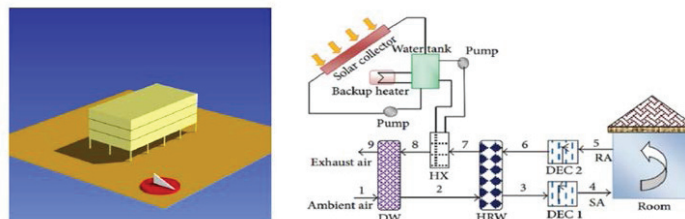


Fig. 1. Building model and SDEC system diagram [23,17].

2.2. Weather data

In this paper, hourly values of cooling load are obtained from a dynamic simulation for the proposed typical building model under different climate locations using EnergyPlus. Therefore, to run the EnergyPlus simulation, an Australian Representative Meteorological Year (RMY) climate data file for each city is required. The Australian Representative Meteorological Year data is the typical weather data developed for the Australian Greenhouse Office for use in complying with Building Code of Australia. It is supplemented by solar radiation estimated on an hourly basis from earth-sun geometry and hourly weather elements [24].

2.3. Key performance indicators

The performance analysis is based on the evaluation of a number of key performance indicators. These include system COP, annual primary energy consumption, energy savings, and CO₂ emissions reduction.

COP is used for evaluating the HVAC system efficiency. It is defined as the ratio of the system cooling capacity to the total HVAC system energy input [20]. For a conventional vapor compression VAV air conditioning system, the COP is expressed by the following equation:

$$COP_{Conv} = \frac{Q_C}{W_{in}} \quad (1)$$

Where Q_C is the refrigeration cooling effect in kW; W_{in} is the system total electric energy input in kW. For the SDEC HVAC system, the system COP can be defined as:

$$COP_{des} = \frac{Q_C}{Q_{reg}} = \frac{m_s \times (h_o - h_s)}{Q_{Solar} + Q_{Aux}} \quad (2)$$

Where Q_{reg} is the energy input for driving the system in kW; Q_{Solar} is the solar gain from solar collectors in kW; Q_{Aux} is the heat energy input of the auxiliary heater in kW; m_s is supply air mass flow rate in kg/s; h_o is the enthalpy of outside air in kJ/kg; and h_s is the enthalpy of supply air in kJ/kg. The COP is counted only when the main cooling equipment (desiccant wheel or chiller) is in operation for each time step.

Primary energy is the total electric energy consumed by the whole air conditioning system. For the conventional VAV system, the primary energy consumption is defined as:

$$E_{p,Conv} = E_{air} + E_{hyd} \quad (3)$$

Where E_{air} is the conventional system air side electricity energy consumption in GJ; E_{hyd} is the electric energy consumption of hydronic equipment in GJ. For the SDEC system, the primary energy consumption is defined as:

$$E_{p,des} = E_{air} + E_{hyd} + E_{Aux} \quad (4)$$

Where E_{Aux} is the primary energy consumption by the auxiliary heater in GJ. The annual energy savings can be expressed as:

$$E_{Saved} = E_{p,Conv} - E_{p,des} \quad (5)$$

The reduced CO₂ emission is calculated using the following equation:

$$CO_2(reduced) = CO_2factor \times E_{Saved} \quad (6)$$

Where $CO_2 factor$ is the emission factor for electricity consumption in kg CO_2 -e/kWh [25].

2.4. System design parameters

The key design input parameters for the conventional VAV system and the SDEC system are summarized in Table 1 and Table 2 below.

Table 1. System design parameters for VAV system.

Parameters	Input data	Parameters	Input data
Supply fan efficiency	0.7	Chiller COP	3.5
Supply fan delta pressure	500 Pa	Condenser type	Water cooled
Return fan efficiency	0.7	Pumps rated head	179 kPa
Return fan delta pressure	500 Pa	Boiler type	Hot water boiler
Design supply air temperature	12.8 °C	Boiler fuel type	Electricity
Boiler efficiency	0.8	Reheat coil type	Hot water

Table 2. System design parameters for SDEC system.

Parameters	Input data	Parameters	Input data
Regeneration fan efficiency	0.7	Solar collector area	760 m ²
Regeneration fan delta pressure	500 Pa	Backup heater fuel type	Electricity
Design supply air temperature	18 °C	Backup heater efficiency	1
Reheat coil type	Electric	Backup heater capacity	100 kW
Pumps rated head	179 kPa	Storage tank volume	3.6 m ³
Solar collector type	Flat plate	Collector loop pump rated flow rate	3 kg/s
Regenerative pump rated flow rate	2.4 kg/s	Regeneration heater rated capacity	300 kW
DW nominal air flow rate*	19 m ³ /s	DW nominal air face velocity	4 m/s
DW nominal electric power	100 W	Regeneration temperature	50 °C
Heat exchanger (HX) type	Flat plate	HX nominal supply air flow rate*	19 m ³ /s
HX nominal secondary air flow rate*	19 m ³ /s	Ratio of supply to secondary hA values	1
Collector optical efficiency η_0	0.753	Recirculating water pump power	50 W
Collector heat loss coefficients C_1	-5.2917	Direct evaporative cooler coil efficiency	0.9
Collector heat loss coefficients C_2	0.00638	Regenerative hot water inlet temperature	75 °C

*Note: The DW and HX nominal air flow rate for Darwin is 22 m³/s.

2.5. Building model validation

To validate the building model, a comparison of the energy performance between the referenced VAV system and the base case results provided by Daly et al. [26] is undertaken. The results demonstrate that these two scenarios

have similar end use energy intensity and percentage for each component item, indicating the model has been properly created.

3. Results and discussions

3.1. Annual building loads

From the model, it is found that Darwin has the highest annual building cooling load (400 MWh). This is followed by Brisbane, nearly 300 MWh. The minimum annual building cooling load happens in Hobart, which is just about 180 MWh. While for the annual building heating load, Canberra has the highest annual heating requirement with approximately 1600 kWh. Hobart, Melbourne and Adelaide also have obvious heating demand at 950 kWh, 450 kWh, and 200 kWh respectively. On the contrast, there is no heating requirement in Darwin and very little heating demand in Brisbane and Sydney. It should be noted that the heating load is much less than the cooling load even for cold winter climate zones such as Canberra, Hobart and Melbourne. This is because for this type of office building, the internal plug loads such as lighting and equipment can offset a large amount of heating demand. This can also be found in the end-use energy consumption breakdown figure.

3.2. System COP

Figure 2 shows the system COP for both the SDEC system and the VAV system. For the referenced VAV system, it is found that in Darwin, the system COP is almost constant at the value of 3, indicating that the VAV system is operating under the cooling mode all year round. While for other cities, especially for Hobart, Canberra and Melbourne, the COP decreases to zero in winter period, which implies that no cooling needed for those periods. For the SDEC system, Darwin has the highest monthly system COP, reaching up to about 7 in the summer and 2 in the winter. Hobart and Canberra have the lowest COP compared with other cities, just below 1 in the summer. The system COP diagram implies that for Darwin, the desiccant system can achieve much higher dehumidifying effect with less backup energy consumption due to substantial solar energy gain. Brisbane has a relatively high COP of 2.6 in the summer and 0.55 in the winter. It is also a cooling dominated climate which requires plenty of cooling demand all year round. However, the solar energy gain in Brisbane is not as sufficiently abundant as Darwin for regeneration purpose and thus requires more backup energy, leading to a lower COP value than Darwin. Adelaide, Perth and Sydney have similar system COP of just below 2 in the summer and nearly zero in the winter, indicating no dehumidification is needed in winter periods in these cities.

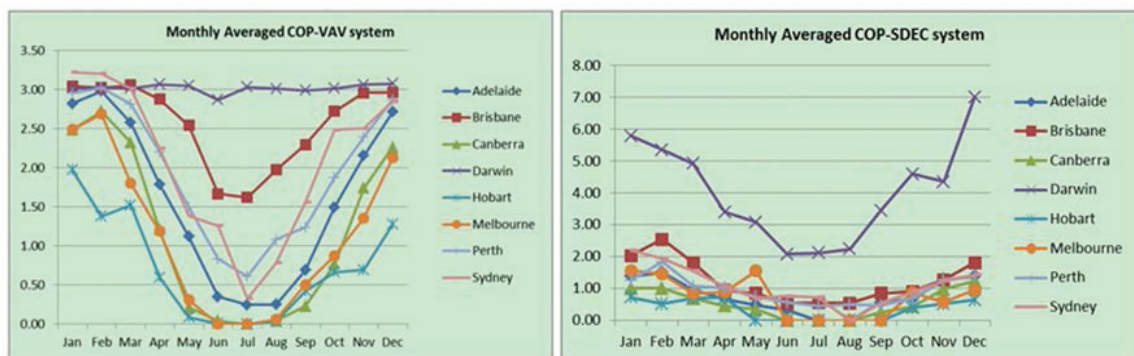


Fig. 2. System COP for both the VAV system and the SDEC system.

3.3. Annual primary energy consumption

Figure 3 illustrates the annual electricity consumption of the two systems. It can be found that the lighting and equipment energy consumption are the same for each city and each HVAC system because of the same load intensity assumed. The main difference lies in the HVAC electricity consumption including fans, pumps, heating component, cooling component, and backup heater etc. It also can be found that for the VAV system, Darwin consumes the most primary energy annually for cooling because of its highest cooling demand. While for the SDEC system, the largest energy consumption is in Brisbane due to the highest backup heater requirement. This is because the cooling demand for Brisbane is the second largest but its solar energy gain is not enough to drive the system. For Darwin, although it has the highest cooling demand, it can also obtain sufficient solar energy which at most of time could provide enough energy to regenerate desiccant, leading to less backup energy requirement than Brisbane. It should be noted that for Hobart and Melbourne, the SDEC system even consumes more energy than the VAV system. This is because the cooling demands for these two cities are significantly lower. Their backup energy is even higher than the VAV cooling energy. Comparing the annual energy consumption of the two systems, it is also observed that the SDEC system can reduce most of the cooling and pumps energy but at the same time consumes more fan electricity. This is because for the SDEC system, the supply air flow rate is larger than that of VAV system in order to provide 100% fresh air, leading to increased fan electricity. Meanwhile, the desiccant wheel and the heat exchanger can recovery substantial of energy for cooling and heating, which results in less evaporative cooler energy consumption.

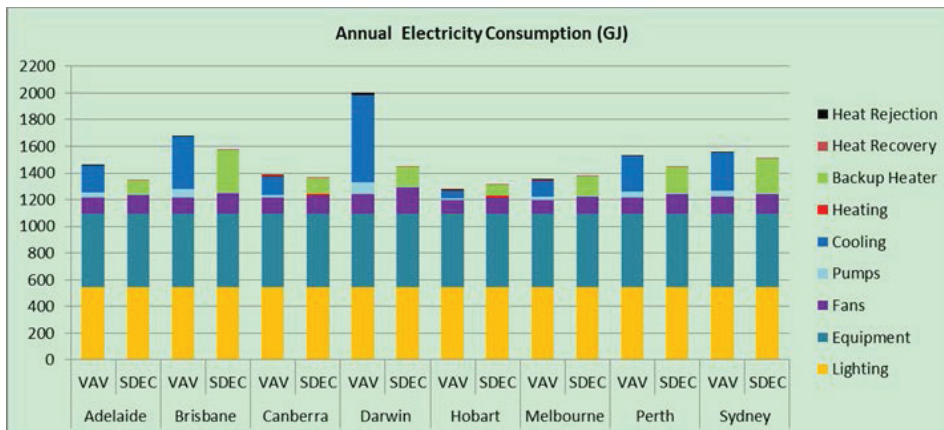


Fig. 3. System annual primary energy consumption.

3.4. Annual energy savings and CO₂ emissions reduction

To evaluate whether the SDEC system is more energy efficient than the conventional VAV HVAC system, one important indicator is the annual electricity energy savings. Table 3 shows the annual primary energy savings and CO₂ emissions reduction potentials of the SDEC system for each capital city. It is clear that Darwin has remarkable annual energy saving advantage of about 557 GJ, with also a total CO₂ emissions reduction of 121 tonnes. Adelaide, Brisbane, and Perth also can achieve a large amount of energy savings and CO₂ emissions reductions. However, for Canberra, the energy savings effect of using SDEC system is not apparent, with less than 20 GJ energy savings and 5.4 tonnes CO₂ emissions reduction per year. While for Hobart and Melbourne, the SDEC system is even not as energy efficient as the conventional VAV HVAC system. It should be pointed out that replacing the VAV system with the SDEC system will consume approximately 40 GJ and 28 GJ more electricity energy per year for Hobart and Melbourne respectively. This is because for Canberra, Hobart and Melbourne, the cooling demand is not high and using SDEC will increase fan consumption dramatically due to the larger supply air flow rate. In addition, the

solar thermal energy gains in these cities are not sufficiently high and thus require more backup energy to drive the desiccant system. The environmental impact is also particularly dramatic for Melbourne because of its high CO₂ emission factor.

Table 3. Annual primary energy savings and CO₂ emission reduction.

City	CO ₂ Emission factor by Electricity (kg CO ₂ -e/kWh)	Annual energy savings (GJ)	Annual CO ₂ emission reduction (kg)
Adelaide	0.72	116.33	23284.6
Brisbane	0.93	106.82	27617.2
Canberra	0.99	19.7	5421.8
Darwin	0.78	556.89	120756
Hobart	0.23	-39.69	-2537.8
Melbourne	1.34	-27.99	-10426.8
Perth	0.83	84.85	19578.3
Sydney	0.99	47.6	13100.5

4. Conclusions

In this paper, an investigation of the system performance of the solar desiccant-evaporative cooling for a typical commercial building has been assessed under a variety of Australian climates. The simulation results have shown that the SDEC system can meet the indoor thermal comfort environment for all 8 Australian capital cities. However, from the energy efficiency point of view, Darwin is more advantageous for the application of the SDEC system, where the SDEC system COP could reach the maximum of 7. In addition, for Darwin, the energy savings potential for replacing the VAV system with the SDEC system is also higher than other cities. Darwin could achieve 557 GJ energy savings per year. This is followed by 116.33 GJ for Adelaide, 106.82 GJ for Brisbane, 84.85 GJ for Perth, 47.6 GJ for Sydney, and 19.7 GJ for Canberra. While for Hobart and Melbourne, the SDEC system even consumes more energy and releases more CO₂ emissions than the conventional VAV system. If the economic factors are taken into account, the application of the SDEC technology would be more beneficial in Darwin. Therefore, the SDEC technology is technically and environmentally more feasible for the climates which have high cooling demand, hot and humid summer characteristics.

References

- [1] A. Boyano, P. Hernandez, O. Wolf, Energy demands and potential savings in European office buildings: Case studies based on EnergyPlus simulations, *Energy and Buildings* 65(2013) 19-28.
- [2] S. Zhu, J. Chen, A simulation study for a low carbon consumption HVAC project using EnergyPlus, *International Journal of Low-Carbon Technologies* 7(2012) 248-254.
- [3] L. Schipper, S. Meyers, R. Howarth, R. Steiner, *Energy efficiency and human activity: past trends and future prospects*, Cambridge University Press: Cambridge, UK, 1992.
- [4] A.M. Baniyounes, Y.Y. Ghadi, M.G. Rasul, M.M.K. Khan, An overview of solar assisted air conditioning in Queensland's subtropical regions, Australia, *Renewable and Sustainable Energy Reviews* 26(2013) 781-804.
- [5] Department of Resources, Energy and Tourism, Geoscience Australia, Australian Bureau of Agricultural and Resource Economics, *Australian Energy Resource Assessment*, Australian Government, Canberra, 2010.
- [6] A. Bahadori, C. Nwaoha, A review on solar energy utilization in Australia, *Renewable and Sustainable Energy Reviews* 18(2013) 1-5.
- [7] A.M. Baniyounes, G. Liu, M.G. Rasul, M.M.K. Khan, Analysis of solar desiccant cooling system for an institutional building in subtropical Queensland, Australia, *Renewable and Sustainable Energy Reviews* 16(2012) 6423-6431.
- [8] K.F. Fong, T.T. Chow, C.K. Lee, Z. Lin, L.S. Chan, Comparative study of different solar cooling systems for buildings in subtropical city, *Solar Energy* 84(2010) 227-244.
- [9] K.F. Fong, T.T. Chow, C.K. Lee, Z. Lin, L.S. Chan, Solar hybrid cooling system for high-tech offices in subtropical climate - Radiant cooling by absorption refrigeration and desiccant dehumidification, *Energy Conversion and Management* 52(2011) 2883-2894.
- [10] K.F. Fong, T.T. Chow, C.K. Lee, Z. Lin, L.S. Chan, Advancement of solar desiccant cooling system for building use in subtropical Hong Kong, *Energy and Buildings* 42(2010) 2386-2399.
- [11] K.F. Fong, C.K. Lee, T.T. Chow, A.M.L. Fong, Investigation on solar hybrid desiccant cooling system for commercial premises with high latent cooling load in subtropical Hong Kong, *Applied Thermal Energy* 31(2011) 3393-3401.
- [12] K.F. Fong, T.T. Chow, Z. Lin, L.S. Chan, Simulation-optimisation of solar-assisted desiccant cooling system for subtropical Hong Kong, *Applied Thermal Energy* 30(2010) 220-228.

- [13] Y. Li, L. Lu, H. Yang, Energy and economic performance analysis of an open cycle solar desiccant dehumidification air-conditioning system for application in Hong Kong, *Solar Energy* 84(2010) 2085-2095.
- [14] Y. Li, H.X. Yang, Investigation on solar desiccant dehumidification process for energy conservation of central air-conditioning systems, *Applied Thermal Energy* 28(2008) 1118-1126.
- [15] H. Li, Y.J. Dai, Y. Li, D. La, R.Z. Wang, Case study of a two-stage rotary desiccant cooling/heating system driven by evacuated glass tube solar air collectors, *Energy and Buildings* 47(2012) 107-112.
- [16] T.S. Ge, F. Ziegler, R.Z. Wang, H. Wang, Performance comparison between a solar driven rotary desiccant cooling system and conventional vapor compression system (performance study of desiccant cooling), *Applied Thermal Engineering* 30(2010) 724-731.
- [17] M.M.S. Dezfouli, S. Mat, G. Pirasteh, K.S.M. Sahari, K. Sopian, M.H. Ruslan, Simulation Analysis of the Four Configurations of Solar Desiccant Cooling in Tropical Weather in Malaysia, *International Journal of Photoenergy* (2014) 1-14.
- [18] S.P. Halliday, C.B. Beggs, P.A. Sleight, The use of solar desiccant cooling in the UK: a feasibility study, *Applied Thermal Engineering* 22(2002) 1327-1338.
- [19] P. Mazzei, F. Minichiello, D. Palma, Desiccant HVAC systems for commercial buildings, *Applied Thermal Engineering* 22(2002) 545-560.
- [20] A.M. Baniyounes, G. Liu, M.G. Rasul, M.M.K. Khan, Comparison study of solar cooling technologies for an institutional building in subtropical Queensland, Australia, *Renewable and Sustainable Energy Reviews* 23(2013) 421-430.
- [21] M. Goldworthy, S. White, Optimisation of a desiccant cooling system design with indirect evaporative cooler, *International Journal of Refrigeration* 34(2011) 148-158.
- [22] S.D. White, P. Kohlenbach, C. Bongs, Indoor temperature variation resulting from solar desiccant cooling in a building without thermal backup, *International Journal of Refrigeration* 32(2009) 695-704.
- [23] ACADS-BSG, ABCB Energy Modelling of Office Buildings For Climate Zoning (Class 5 Climate Zoning Consultancy) Stage 1, 2 & 3, Australian Building Codes Board, Glen Iris, 2002.
- [24] EnergyPlus Weather Data, available online at http://apps1.eere.energy.gov/buildings/energyplus/weatherdata_about.cfm.
- [25] L. Lecamwasam, J. Wilson, D. Chokolich, Guide to Best Practice Maintenance & Operation of HVAC Systems for Energy Efficiency, Council of Australian Governments National Strategy on Energy Efficiency, Department of Climate Change and Energy Efficiency, 2012.
- [26] D. Daly, P. Cooper, Z. Ma, Understanding the risks and uncertainties introduced by common assumptions in energy simulations for Australian commercial buildings, *Energy and Buildings* 75(2014) 382-393.