PV driven dew-point cooling for Australia

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Abstract

Dew-point cooling devices use the principles of evaporative cooling to provide air-conditioning with very high electrical efficiency. Although commercial products are available, they are yet to gain mainstream acceptance in the residential cooling market. One factor has been a lack of clarity around the climates for which they're suitable. This is undoubtedly complicated by the fact that cooling demand varies greatly between different buildings even within the same climate. In addition, the economic benefit due to lower running costs may be off-set by a higher initial purchase price. If dew-point coolers (DPC) are to compete on price alone, any economic benefit needs to be very clearly communicated. A complicating factor is the advent of dedicated solar PV driven, and PV-battery driven air-conditioners. Given that DPC's require less electricity to provide the same cooling, this should translate to a reduction in the required PV-battery system size. Here we analyse the ability of DPC's to provide complete comfort in different combinations of Australian climates and buildings, both for grid-connected and off-grid PV-battery applications, as well as the economics of both these systems in comparison to conventional vapour-compression air-conditioners. Results show that a DPC can provide complete comfort for approximately half the Australian population; that a 5kW grid-connected cooler is economic in key climates at an installed cost of $2000, and that an off-grid PV-battery driven DPC is currently not economically viable.

Keywords: dew point cooling, air-conditioning, solar cooling

1. Introduction

In Australia, rising energy prices have resulted in a 69% increase in residential electricity expenditure during the last decade (Coleman, 2017). Use of residential air conditioners during hot summer afternoons is the main contributor to network peak demand periods (Energy Networks Association, 2014). HVAC energy consumption in residential buildings is estimated to contribute nearly 18% of total emissions (CO_2-e) from the built environment sector (ClimateWorks, 2016).Heat stress is the largest cause of fatalities due to natural hazards in Australia with recent evidence suggesting that the number and severity of such events may be increasing (Steffen & Hughes, 2014). Energy efficient, cost effective cooling solutions that can address these problems would be very valuable to Australian consumers, network utilities and the community in general.

Dew point indirect evaporative coolers (DPC's) can deliver temperatures to the building as low as the dew-point temperature of the incoming air and use only a fraction of the energy required by a conventional vapour-compression air conditioner. In addition, unlike compression air conditioners, whose capacity and efficiency are decreased due to reduced heat rejection capacity on hot summer days, DPC's can operate with higher capacity and efficiency during these periods. Their low energy use also gives them a greater potential to be integrated with a PV energy source and small battery to operate as standalone cooling delivery system. A grid independent PV DPC solution can take the cooling load off the electricity grid and reduce peak energy demand. However, DPC's provide only sensible cooling, they do not remove any humidity from the indoor space and hence may not be appropriate for certain combinations of climates and building heat loads.

The laboratory and in-situ performance of various DPC's has been studied by a number of researchers (see for example (Jradi, 2014) (Ham, 2016) (Pandelidis & Anisimov, 2015) (Bruno, 2011)) and ongoing development is targeted at incremental improvements to the cooling performance, overall efficiency, and in particular, the size and cost, for example through the use of new heat exchange surfaces and manufacturing methods (see for example (Lee., 2013) (Xu, Ma, & Zhao, 2016)). An overview of the fundamentals of indirect evaporative cooling may be

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found in (Glanville, Kozlov, & Maisotsenko, 2011).

Worldwide there are several commercial suppliers of DPC's. Commercially available systems have been, in the most part, targeted at larger scale applications such as warehouses, manufacturing facilities and offices. However, residential scale systems are also beginning to enter the market. In Australia, residential scale DPC systems are yet to reach any measureable penetration into the air-conditioning market which is dominated by the annual sale of approximately 1 million vapour-compression systems (E3 Committee, 2016).

Undoubtedly one of the reasons why DPC's are yet to become more than a novelty for residential buildings is the fact that their performance over a wide range of climates and building designs is still yet to be described. The extent to which they can expand the historical operating range of direct evaporative (swamp) coolers from dry climates to more humid and even tropical locations, given typical occupant comfort levels, is of particular interest.

The second aspect of interest stems from the fact that typical electricity efficiencies of DPC's are 2 to 3 times higher than vapour-compression systems. Obviously by itself this results in a direct saving of electricity and any associated emissions. However, it may be more important for households with a photovoltaic system (either with or without batteries) where purchasing energy from the grid is particularly undesirable (for example due to high electricity costs and low prices paid for excess PV generation fed back to the grid) given that significant cooling use for many households occurs in the late afternoon and early evening. For households not connected to the electricity grid, a small saving in air-conditioner energy use may have big implications for the required size of the electricity generation system; be it a PV-battery system or other form of generation. However, the size of the dedicated PV-battery system required to run a DPC in different climates is highly dependent on the coupling between the pattern of solar availability, the weather, the building physics and the occupant requirement for cooling. There is no common 'rule-of-thumb'.

Thus, this study aims to address three questions;

1. For what combination of Australian climates and residential buildings can a commercial DPC provide complete annual (cooling) comfort if connected to the electricity grid?
2. What size PV-battery system is required to operate a stand-alone (grid independent) DPC in different combinations of Australian climates and buildings?
3. What is the maximum installed cost of a DPC to be cost neutral with a vapour-compression system in different climates and buildings?

For the off-grid PV-battery driven system we focus on economics as the primary performance parameter since theoretical measures such as annual efficiencies and PV utilization have little relevance to the overall viability which is ultimately governed by the economics. The modelling method used is described in Section 2. The three questions above are addressed in Sections 3.1, 3.2 and 3.3 respectively. Section 4 discusses the results including the market potential of DPC's in Australia.

2. Modelling method

The simulation model as described in (Goldsworthy M. , 2017) was used with selected modifications. This model simulates the combined building and cooling system over a year at intervals of 10 minutes using representative climate data for locations across Australia. It consists of i) a building model based on a uniform temperature and humidity air node coupled to transfer function models of external walls, ceiling and roof cavity; ii) a photovoltaic and lithium ion battery charge/discharge model, iii) a vapour-compression air-conditioner model based on performance curves (Cutler, 2013) and using the Bypass Factor approach, and iv) weather and radiation data processing models. To this model a dew-point cooler sub-model was implemented as described below.

2.1. Dew-point cooler model

The dew-point cooler (DPC) performance model is based on curve fit of data from experimental tests of a commercial DPC in the Controlled Climate Test Facility at CSIRO Energy Technology (Brandenburger, 2017). Tests were conducted with inlet air dry and wet bulb air temperatures in the ranges 32 to 40°C and 20 to 28°C such that the inlet air wet-bulb depression was between 5 and 17°C. The resulting performance was characterised in terms of two quantities; the dew-point effectiveness and electrical coefficient of performance (COP), given by;

$$\varepsilon_{dp} = 0.364 + 0.0172T_{in\_wb} \quad \text{(eq. 1)}$$

$$COP = -0.665 + 1.09(T_{in} - T_{in_{wb}}) \quad \text{(eq. 2)}$$

where dew-point effectiveness is defined according to;

$$\varepsilon_{dp} = \frac{T_{in} - T_s}{T_{in} - T_{in\_dp}} \quad \text{(eq. 3)}$$

T_{in}, T_{in_wb} and T_{in_dp} are the inlet air dry bulb, wet bulb and dew-point temperatures respectively and T_s is the supply air temperature to the building. The Root Mean Square Error over the test range was 0.014 for the dew-point correlation and 0.203 for the COP correlation.

These correlations are based on a fixed secondary exhaust mass flow fraction of 0.4. Higher exhaust fractions typically result in lower supply air temperatures which is off-set by the lower supply air flow rate. Hence there is a trade-off between cooling capacity and supply air temperature. The presence of an exhaust air stream means that the DPC cannot operate with 100% recirculation of building air without also drawing outside air into the building. Thus, here a fixed fresh air flow rate equal to the secondary exhaust flow rate was used for all simulations. Hence the inlet air to the DPC was a mixture of return air and ambient air. A fixed supply air flow rate of 1500kg/hr corresponding to a 5kW (sensible) cooling capacity at air inlet conditions of $T_{in} = 35°C, T_{in\_wb} = 24°C$ was used for all simulations.

2.2. Control strategy

The cooling control strategy is summarised in Figure 1. This consisted of 3 temperatures levels each for day cooling and night cooling. For day-cooling (awake hours) the highest temperature level (27°C in the figure), referred to here as the ‘trigger temperature’ T_t, was compared to the indoor *apparent* temperature $\tilde{T}_b$. Apparent temperature combines both temperature and humidity and gives a better indicator of thermal comfort. Here the method of Steadman (Steadman, 1984) was used to calculate apparent temperature. If $\tilde{T}_b > T_t$, then cooling was activated and the cooler cycled on/off to maintain the building temperature between the upper and lower apparent temperature set-points $\tilde{T}_u$ and $\tilde{T}_l$. The signal that indicates that cooling has been ‘tripped’ was reset at 6am each day. This models, in effect, a ‘resetting’ of the occupant memory of air-conditioner use. (Note though that the cooler could still turn off prior to this if the indoor temperature was within the set-points.)

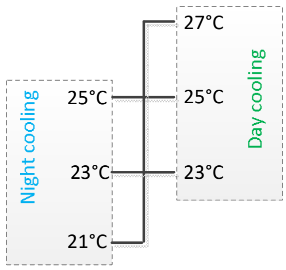

Figure 1 Apparent temperature threshold levels for air-conditioning control.

2.3. Residential building models

To assess the ability of the DPC to provide cooling for different combinations of climate and buildings, multiple building models were developed by varying the thermal characteristics of the building envelope. The ‘building’ models were based on a single room with fixed floor area of 50m², pitched roof, and a single window with external eave shading on one of the four walls. The thermal characteristics of this single room were varied to construct 2000 different building models composed from a random selection of the parameter values in Table 1.

These parameter values are the same as those described in (Goldsworthy, 2017) and, with the exception of orientation and wall construction type, were chosen to correspond to a notionally ‘above average’ value and a notionally ‘below average’ value for Australian houses. These values are not intended to represent the extrema, but rather plausible ranges that cover the majority of residential buildings. As outlined in (Goldsworthy, 2017), these parameter values were selected with reference to the published literature where possible.

For each climate zone, three annual simulations were run for each building model; one for the building with dew-point evaporative cooler, one for the same building with a grid-connected vapour-compression air-conditioner with the same total cooling capacity, and one for the building without any air-conditioning. In addition, for the off-grid DPC cases simulations with varying PV and battery sizes were also run. Typical Meteorological Year weather data files for the 69 climate zones (Department of Environment and Energy, 2018) that cover all of Australia were employed. As described in Section 2.4, the model predictions from each building simulation were weighted according to the estimated proportions of the different building types in each climate zones based on a housing stock model.

Tab. 1: Building model thermal parameter values and distribution

Variable	Parameter values	Frequency of parameter value in a given climate zone
Internal zone thermal capacitance (ratio of air thermal capacitance)	5x, 15x	Uniform likelihood
Infiltration rate	0.5,2.0 a/hr	Lower infiltration rate occurrence proportional to fraction of 'performance buildings' derived from housing stock model (DEWHA, 2008)
Internal load profile (morning and evening peaks)	Average daily load: Low: 4.7/1.95/0.34 W/m² (sensible/latent/radiative) High: 9.4/3.9/0.67 W/m² (sensible/latent/radiative)	Uniform likelihood
Building aspect ratio	1:1, 2:1	Uniform likelihood
Window orientation (degrees from Nth)	0, 45, 90, 135, 180, 225, 270, 315°	Uniform likelihood based on (Whitsed, 2013)
Ceiling insulation	None, R3	Based on housing stock model (DEWHA, 2008)
Roof solar absorptivity	0.3, 0.9	Uniform likelihood based on (Whitsed, 2013)
Wall construction (thermal mass)	Light (weatherboard), Medium (brick veneer), Heavy (double-brick)	Based on housing stock model (DEWHA, 2008)
Wall solar absorptivity	0.3, 0.75	Uniform likelihood
Window to floor area ratio	10%, 20%	Uniform likelihood
Window type	Single glazed, double glazed with shading from external roof eave.	Double glazed window occurrence proportional to fraction of 'performance buildings' derived from housing stock model (DEWHA, 2008)
Wall insulation	None, R2	Based on housing stock model (DEWHA, 2008)

2.4. Building model weighting factors

Here we applied a weighting factor to the simulation results to reflect the estimated distribution of actual buildings with the various characteristics in each climate zone. That is, for a specific performance metric Y, the weighted average of the performance metric for a given climate zone *cz* was calculated according to;

$$\langle Y \rangle_{cz} = \sum_{b=1}^{N_b} Y_{cz} W_{b,cz} \qquad \text{(eq. 4)}$$

Where $W_{b,cz}$ is the weight factor for a building model *b* and climate zone *c*. $W_{b,cz}$ was calculated according to;

$$W_{b,cz} = \frac{N_b}{\sum_b \prod_v W_{v,b}} \prod_v W_{v.b} \qquad \text{(eq. 5)}$$

where $W_{v,b}$ is the weight factor for the specific building parameter value *v* for the building *b*. The building parameter weight factor $W_{v,b}$ was calculated differently for each building parameter as described below.

For the internal thermal capacitance, internal load profile, building aspect ratio, window orientation, wall and roof solar absorptivity and window to floor area ratio, a uniform weighting factor ($W_{v,b} = 1$) was applied. That is, we assumed a uniform distribution of buildings with parameter values as listed for these variables. With the exception of roof solar absorptivity and window orientation, this assumption was made in the absence of other information on the distributions of these variables in actual buildings. For roof solar absorptivity and window orientation a recent study using satellite data to investigate the possible impact of building regulations on roof colour and house orientation found no consistent evidence for a difference between buildings built pre and post introduction of more stringent energy efficiency standards (Whitsed, 2013). While this does not necessarily mean that window orientation and roof colour are uniformly distributed across buildings and locations, in the absence of detailed data describing these parameter variations, here we assume uniform distributions of these parameters also.

For ceiling insulation, wall insulation and wall construction, data from a National Housing Stock model (DEWHA, 2008) was used to calculate the fraction of buildings with and without ceiling and wall insulation for three different base construction types; lightweight, medium-weight and heavyweight in each climate zone for the year 2020. The proportions of buildings in each classification for each climate zone were used to calculate the weight factors $W_{v,b}$ for a given building model ensuring that the weights for each variable were normalized to have a maximum of 1 over all the building models.

For natural infiltration rate and window type, the proportion of 'performance' buildings (i.e. buildings built post the introduction of more stringent energy efficiency standards in each state) in each climate zone was used to calculate the weight factors. Higher weightings were assigned to the building models with the lower infiltration rate and with double glazed windows based on the proportion of performance buildings in the climate zone.

2.5. Comfort performance metrics

Since we expect that the DPC will not provide complete comfort in all building and climate combinations, we define an occupant discomfort metric as follows. The annual degree of discomfort (dd_c) is calculated as the cumulative difference between the indoor apparent temperature $\tilde{T}_b$ and the upper temperature threshold $\tilde{T}_u$ for the given time of day.

$$dd_c = \sum max(\tilde{T}_b - \tilde{T}_u, 0)\Delta t/24 \qquad \text{(eq. 6)}$$

Here Δt is the time interval of the simulation in units of hours. We use $\tilde{T}_u = 25°C$ for awake hours (6am to 10pm) and $\tilde{T}_u = 23°C$ for sleeping hours (10pm to 6am).

Comparison of the dd_c metric with the conditioning control strategy described in Section 2.2 reveals that even a cooling system with unlimited capacity generally will not lead to a precisely zero discomfort metric over the year because of the use of the trigger temperature. In practice this could be attributed to the accumulated periods of time over a year between the onset of some mild occupant discomfort and the action of switching on cooling. Because of this, if the DPC system achieves $dd_c < 100$ we considered this to correspond to full (cooling) comfort for that particular case.

2.6. Economics

Economic comparisons were based on the estimated maximum purchase cost of the DPC (C_{DPC_max}) to achieve net zero cost over the lifetime of product, assuming a cooling device needed to be purchased. For a grid connected DPC this is calculated by solving the following equations;

$$\begin{gathered} A_t = A_{t-1}(1+i)^t - (RC_{VC} - RC_{DPC})(1+rpi)^t \\ A_0 = C_{DPC\_max} - C_{VC}, \quad A_{10} = 0 \end{gathered} \qquad \text{(eq. 7)}$$

where $i = 5\%$ is the investment interest rate, $rpi = 1\%$ is the real retail electricity annual price increase, *t* is the year sense installation, RC_{VC} and RC_{DPC} are the calculated annual running costs of the grid connected vapour compression and dew-point cooler respectively, and C_{VC} is the purchase cost of the vapour-compression system. This equation models an initial loan required to purchase the DPC with annual electricity cost savings used to make repayments. The maximum size of the initial loan (i.e. the purchase cost of the DPC) that achieves payback after 10 years is calculated.

For the off-grid comparison a similar approach was used. The maximum purchase cost of the DPC to achieve payback over the lifetime is calculated by solving the equation;

$$A_t = A_{t-1}(1+i)^t - RC_{VC}(1+rpi)^t + \left(0.5C_B + C_{DPC\_max} - C_{VC}\right)\delta(t-10)$$
$$A_0 = C_{PV} + C_B + C_{DPC\_max} - C_{VC},\ A_{20} = 0 \quad \text{(eq. 8)}$$

This equation also assumes a cooling device needs to be purchased and models an initial loan to purchase the DPC and PV-battery system with annual electricity cost savings used to make repayments. However, in this case the payback is calculated over 20 years with purchase of a replacement DPC and battery after 10 years.

Additional economic parameters used in the model are summarized in Table 1.

Tab. 2: Summary of economic parameters used

Category	Value	Details
Electricity tariff	Peak/off-peak/shoulder: 47c/kWh / 11c/kWh / 20 c/kWh	Peak: M-F 2pm-8pm Off-peak: 10pm-7am 7 days
Real retail electricity price increase	1% per annum	(Jacobs Pty Ltd., 2016)
5kW vapour-compression system installed cost	$1500	Compiled from multi-sources
Vapour-compression system lifetime	10 years	(BIS Shrapnel, 2014)
DPC lifetime	10 years	Estimated
PV installed cost	$1.5 to $3.4 /Watt (State dependent)	(Solar Choice, 2018) 2kW system
Battery system installed cost	$1580/kWh	(Solar Choices, 2018) 3kWh system
PV-battery lifetime	20 year (PV), 10 years (battery)	(SolarQuotes, 2017)
Battery system 10 year replacement cost reduction	50%	(Brinsmead, 2015)

3. Results

3.1. Comfort delivery (grid connected DPC)

The question of whether the DPC can maintain comfort conditions inside the building in different climates if sufficient electricity is available was considered first. That is, the ability to create comfortable conditions with no constraint on available electricity given that the DPC provides sensible cooling only.

Figure 2 shows a map of Australia with capital cities locations marked. The tropic of Capricorn is located at approximated 23.4°S latitude; areas north of this line typically have tropical climates though far inland areas often have low humidity and may be arid. Areas south of this line have more temperate climates though inland areas generally have hot, dry summers.

The diagonal hatched region indicates the climates where the DPC provides complete cooling comfort over the year for less than 20% of residential dwellings. In this region, complete comfort was achieved in only a small fraction of buildings and so DPC's operating in this region are deemed unlikely to provide a complete cooling comfort solution for most occupants, almost regardless of the building design. The cross-hatched region indicates the climates where the DPC provided a complete cooling comfort solution for more than 20% of residential dwellings. Whether complete comfort is achieved depends on the particular thermal design of the building, internal heat loads, local climate and, in practice, the occupant comfort tolerance. This region includes most of the major population centres. Overall the DPC is estimated to be able to provide a complete cooling solution for 45% of Australian households or over 10.5 million people.

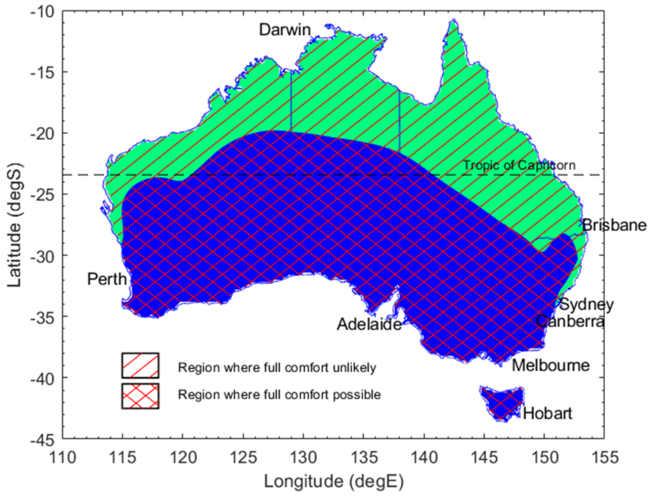

Figure 2 Regions where complete cooling comfort using the DPC are unlikely (lines) and possible (cross hatch) based on <20% and >20% (respectively) of the simulated buildings achieving complete cooling comfort.

Although complete comfort was not achieved for certain building and climate combinations, this does not necessarily mean that comfort levels were not substantially improved by the DPC for these cases. Figure 3 compares the number of daytime operating hours as a function of internal apparent for one particular building for the sub-tropical climate of Brisbane (left) and the temperate climate of Melbourne (right). The internal temperatures are shown for the building with the DPC operating, and also for the building with no cooling at all. The particular building chosen had an annual degree of discomfort with the DPC very close to the median for all of the buildings in both Brisbane ($dd = 520$) and Melbourne ($dd = 25$). It had an insulated brick veneer construction, was relatively well sealed, and had a North-East facing double glazed window. The number of hours corresponding to each apparent outside temperature is also shown.

In both climates the DPC substantially improved the comfort level in the building over the case with no cooling. However, for Brisbane there were a considerable number of hours where the daytime comfort level remained above the upper threshold of 25°C apparent temperature. This resulted from the inability of the DPC to provide building supply air temperatures low enough to result in comfortable indoor conditions when the outside relative humidity was high. Whether or not these conditions are acceptable of course depends upon the individual occupant preferences. The analysis here assumes that such conditions are unacceptable.

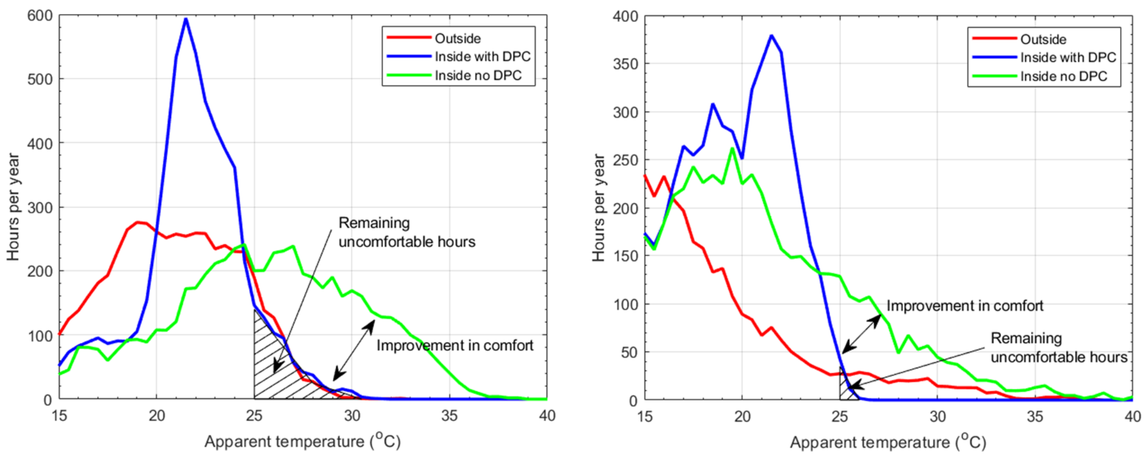

Figure 3 Apparent temperature frequency histogram showing outside temperature and inside temperature in the building with and without DPC for 1 selected building for sub-tropical climate of Brisbane (left) and temperate climate of Melbourne (right).

3.2 PV-battery system sizing for off-grid DPC

The second question of interest is the size (i.e. generation and storage capacities) of the PV-battery system required to operate the DPC independent of the grid in different climates and buildings. Simulations were run with combinations of three different PV array rated output (300W, 600W and 900W) corresponding to 1, 2 or 3 standard crystalline silicon modules, and 5 different battery storage capacities between 0.2kWh and 3kWh.

At the nominal rated condition the DPC has a 5kW capacity and COP=11.3, hence an electrical power draw of 440W. Thus, for the case with a single PV module operation relied on battery discharge to operate at full capacity at the rated condition. These battery capacities correspond to between 20 minutes and 5 hours of operation with 75% discharge.

The lowest overall cost PV-battery system that allowed the DPC to satisfy the comfort criteria was determined for each combination of building and climate zone. The resulting weighted fraction of buildings with different combinations of PV and battery system are shown in stacked bar charts in Figure 4 for selected climate zones.

For example, for the Perth climate zone, approximately 32% of buildings reached comfort with a 600W PV system and 35% with a 900W system. Approximately 28% of buildings required a 3kWh battery, another 17% a 1.5kWh battery, a further 14% a 1kWh battery and 7% a battery of 500Wh or smaller.

Where the total height of the bar is less than 1, the missing fraction of buildings corresponds to those buildings where none of the modelled combinations of DPC and PV-battery system achieved the required comfort conditions. This may have been due to either insufficient electrical power available, or the inability of the DPC to provide comfort conditions for those buildings in the given climate.

While the required number of PV modules and battery system capacity is of general interest (for example from the perspective of the physical space required for these devices), ultimately it is the economics of the overall system that is the main consideration. This is discussed below.

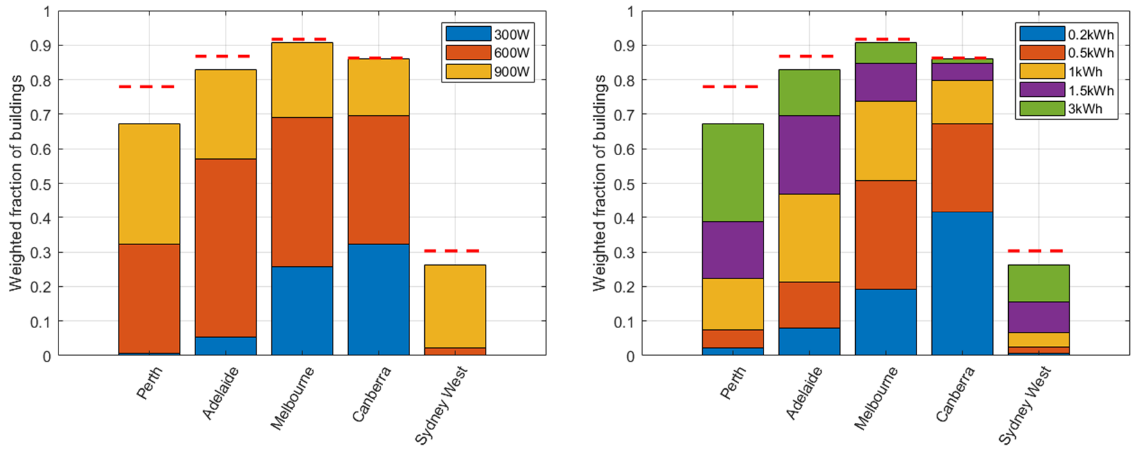

Figure 4 Weighted fraction of buildings and corresponding required PV (left) and battery (right) size to achieve equivalent comfort to grid-connected DPC for selected locations. Where totals sum to less than 1, the missing fraction corresponds to buildings that required a PV-battery system larger than modelled or where comfort could not be achieved with the DPC.

3.3 Economics

The third question of interest is the economics of both the grid-connected and the off-grid PV-battery DPC in different climates and buildings. The economic viability can be calculated in comparison to different baselines and using different methods. Here we use a grid-connected vapour-compression system as the baseline for both cases. As noted above, for the off-grid system the PV-battery is sized to satisfy the comfort conditions (if possible); for climate-building combinations where the comfort conditions are not met, the economics were not calculated.

To evaluate economic viability the lifetime cost including the capital for the initial investment and the operating costs are compared to calculate the maximum installed cost of the DPC that achieves break even (or cost neutrality) with the reference system over the operating life. For the grid-connected DPC, the operating life was taken as 10 years while for the off-grid system, twice this period was assumed allowing for battery and cooling system replacement at the 10 year mark. Economic parameters used are listed in Table 2.

Figure 5 (left) shows a boxplot of the maximum installed cost of the grid-connected DPC to achieve breakeven with the grid-connected vapour-compression air-conditioner over the operating life for the buildings that achieve full comfort and for selected climates. Higher costs are preferable sense these indicate that the DPC can cost more to purchase and still deliver savings over the lifetime. In all cases the maximum cost is at least greater than the cost of the vapour-compression air-conditioner; this simply confirms that the DPC costs less to run than the vapour-compression air-conditioner.

The most favorable locations from an economic perspective are Perth, Adelaide and Western Sydney. This is despite the fact that a significant proportion of buildings in Western Sydney did not reach full comfort with the DPC. That is, for those buildings where full comfort was met, the economics were more favourable if the location (and building) required more cooling.

Figure 5 (right) shows the average maximum installed cost of the grid-connected DPC as a function of the annual apparent temperature cooling degree days for each climate zone. Blue circles represent climate zones where more than 50% of buildings reached full comfort with the DPC; red crosses climates zones where fewer than 50% of buildings reached full comfort. The installed cost of the DPC can be higher and the system still achieve cost neutrality over the lifetime for climates with a large cooling demand; though if the demand is too high, the DPC struggles to provide comfort for many buildings.

The distinction between climates where the DPC can provide full comfort for the majority of buildings and those where it cannot is not clear cut in terms of the number of cooling degree days. This is because additional factors such as the timing of the cooling demand, the relative portion of the load due to irradiance, as well as the ambient humidity levels, all affect the ability of the DPC to provide full comfort.

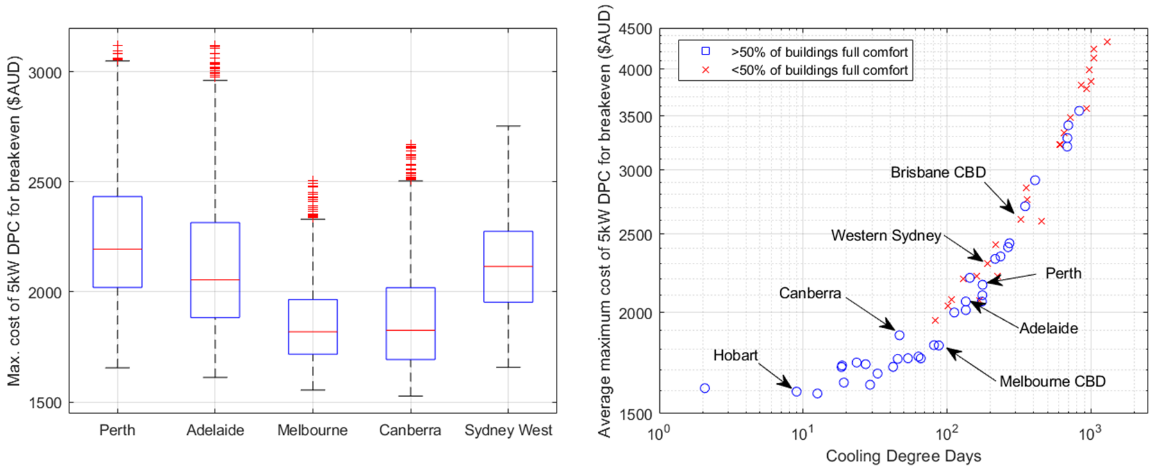

Figure 5 Left: Boxplots showing maximum purchase price of a 5kW DPC to achieve net zero cost over the lifetime of the product for selected locations for buildings reach full comfort assuming financing at 5% interest. Right: Weighted average maximum purchase price as a function of the number of apparent temperature cooling degree days in the climate zone.

For the of the off-grid PV-battery driven DPC case economics were also calculated in comparison to the grid-connected vapour-compression air-conditioner. Figure 6 shows boxplots of the maximum installed cost of the off-grid DPC to achieve breakeven over the lifetime. Note that the installed cost is only that of the DPC; the PV-battery purchase costs were already factored into the calculation. Similarly to above, results are only shown for buildings where the off-grid DPC could provide full comfort.

In this case, for the vast majority of buildings the maximum installed cost of the DPC must be less than $1500 which is the cost of the vapour-compression system. For example, for Canberra, if the DPC was to cost between $450 and $1100, then for 50% of buildings (the region covered by the blue box in the figure) an off-grid PV-battery driven DPC system would be cost neutral with a grid-connected vapour-compression system. In some cases the maximum installed cost is negative. This means that the cost of the PV-battery system alone is too high to achieve cost neutrality, regardless of the cost of the DPC.

Based on these results, at present an off-grid PV-battery driven DPC for residential cooling is not economic. This is essentially due to the number of operating hours where cooling is required in a residential building for the locations where the DPC can provide full comfort, and the relatively high cost of the PV-battery system. Key factors likely to improve the economic prospect include decreasing the cost of battery storage, increasing the hours of operation, and any financial incentives that offset the purchase cost of the system.

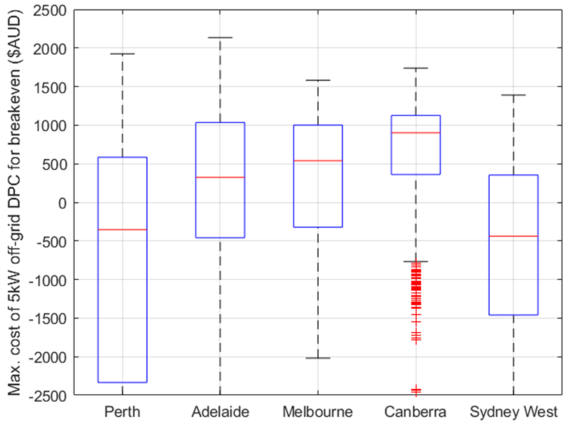

Figure 6 Boxplots showing maximum purchase price of a 5kW DPC in an off-grid PV-battery driven system to achieve net zero cost over the lifetime of the product for selected locations for buildings reach full comfort assuming financing at 5% interest. (Note: battery and PV costs are considered separately.)

4. Discussion

The analysis describe here was based on simulations of a single year using Typical Meteorological Year climate data derived from long term meteorological records covering the period 1967-2012. The economic analysis then assumed the single year simulation results applied for the 10 and 20 year operating lifetimes. However, evidence shows that climate change is increasing the daytime maximum and overnight minimum temperatures across most of Australia (Bureau of Meteorology, 2018). This is resulting in an increase in the required operating hours of cooling systems and hence is likely to improve the economics of the DPC; both because of the greater potential for running cost savings, but also because, under hotter conditions, the comparative performance of the DPC improves relative to vapour-compression systems, provided humidity does not also increase. Unfortunately projections on future humidity levels are uncertain with no clear consensus between various climate models (Climate change in Australia; projections for Australia's NRM regions, 2018). A future topic of research is to assess the impact of climate change on DPC suitability and economics through the use of future climate data in the simulations.

An important factor in the economic comparison that was not considered here is the fact that many conventional air-conditioners are reverse cycle, hence they provide a heating function as well. In most of the less humid, southern climates where the DPC could provide a complete (cooling) comfort solution for the majority of buildings, winter heating would also be required. To properly account for this in the economic analysis it would be necessary to assume a combined heating system with the DPC. We have not done this here since there are no such systems currently available commercially for residential buildings. However, the impact of climate change is relevant here also. For example (Wang, Chen, & Zhengen, 2010) estimate that under a 'moderate' climate change scenario (A1B), the annual heating load will reduce by 36% in Melbourne and 74% in Sydney by 2050. At the same time, the cooling load is predicted to increase by 90% in Melbourne and 120% in Sydney. The reduction in heating demand is expected to have the most impact on the economics if it means heating is no longer required at all, but it may also be relevant in cases where it becomes economic to provide the small amount of heating required using a low purchase cost device such as a convection heater.

The suitability and economic viability of dew-point cooling is essentially guided by the interaction between three factors, the climate, the building and the occupants. The analysis here considered varying climates and building thermal parameters. However, the occupants play a central role in determining the overall energy use of a building, as well as the energy use for air-conditioning. Variations in energy use can arise due to fundamentally different comfort preferences, but they can also be strongly influenced by other considerations such as the financial cost of using air-conditioning. In seeking to assess a relatively new, efficient technology for providing comfort, here our interest is in occupants ideal comfort levels, not actual current air-conditioning usage behaviors. We have used fixed day and night-time apparent temperature comfort thresholds of 25°C and 23°C respectively. Some occupants may find these conditions uncomfortable, either too hot or too cold. By way of comparison, at 60% relatively humidity, an apparent temperature of 25°C corresponds to an air temperature of 24°C. According to the ASHRAE comfort standard (ASHRAE, 2010), for a seated person with summer clothing, at the same humidity the air temperature corresponding to the lowest percentage of persons dissatisfied is 25.3°C (neglecting the effects of radiant temperature and wind speed). Hence the value we used is likely toward the cooler end of most individual's ideal for comfort.

Finally we have used data from laboratory testing of a commercial DPC. In operation it is possible that performance may be slightly reduced, for example we have not considered ducting heat losses or performance degradation over time. On the other hand similar effects are also likely to apply to the conventional technology as well. Characterisation of the long term performance of DPC in residential installations is a topic of future investigation.

5. Conclusion

A commercially available dew-point cooling system with a rated electrical efficiency over 10 can provide complete (cooling) comfort in most residential buildings in the southern region of Australia covering the capital cities of Perth, Adelaide, Canberra and Melbourne. This corresponds to 46% of households or over 10 million people. In the sub-tropical and tropical locations DPC can provide significantly improved comfort, but higher humidity levels mean that complete comfort is unlikely for most buildings in these climates.

The economics of a grid-connected DPC varying across climates and buildings, but are most favourable in Perth, Adelaide and Western Sydney where a 5kW DPC with an installed cost of $2000 or less would be cost competitive at present with a vapour-compression cooler for the majority of households.

For an off-grid PV-battery driven DPC, the required size of the PV array and battery system also varies across climates and buildings. However, the relatively high cost of the PV-battery system and the relatively small number of operating hours over a year in a residential application mean that the economics of an off-grid DPC system are not favourable at present.

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